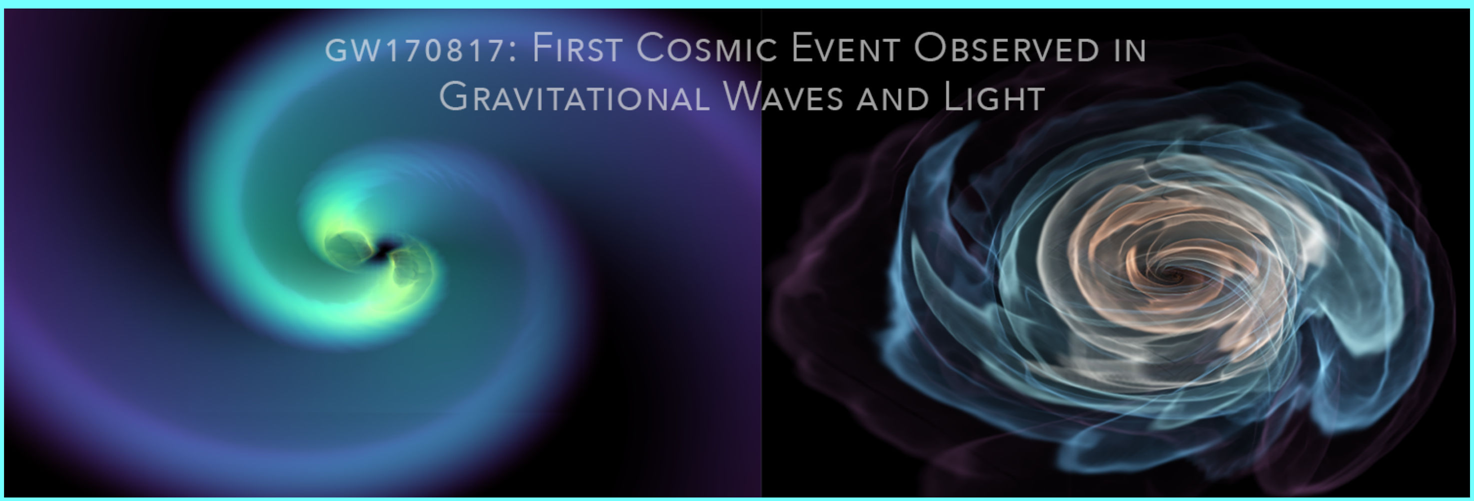
Detection of Gravitational Wave Transients in the Era of LSST

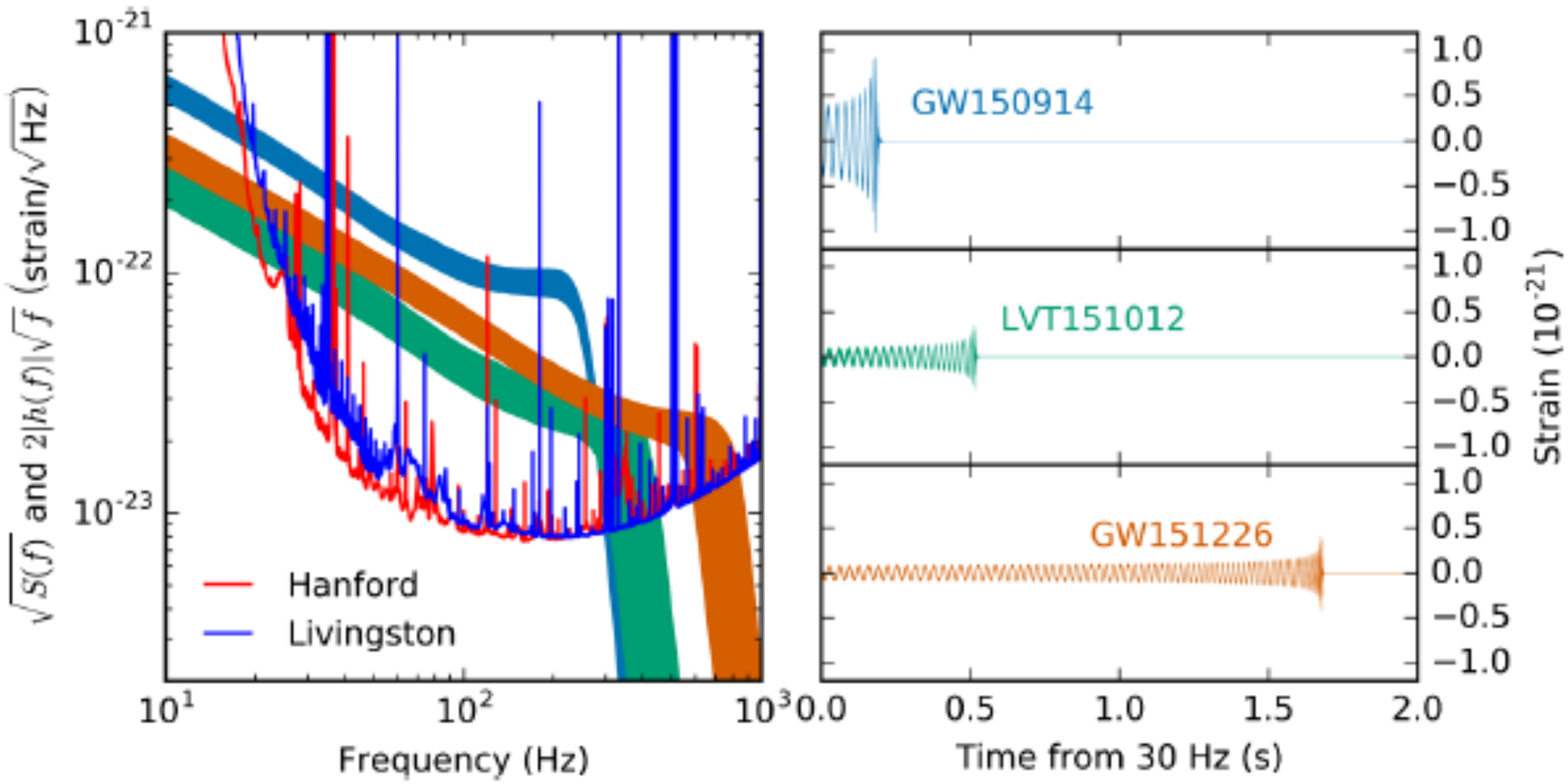
Alan J Weinstein
LIGO Laboratory, Caltech
for the LIGO and Virgo Collaborations

LSST-2019, Tucson AZ, August 15, 2019

LIGO-G1901461

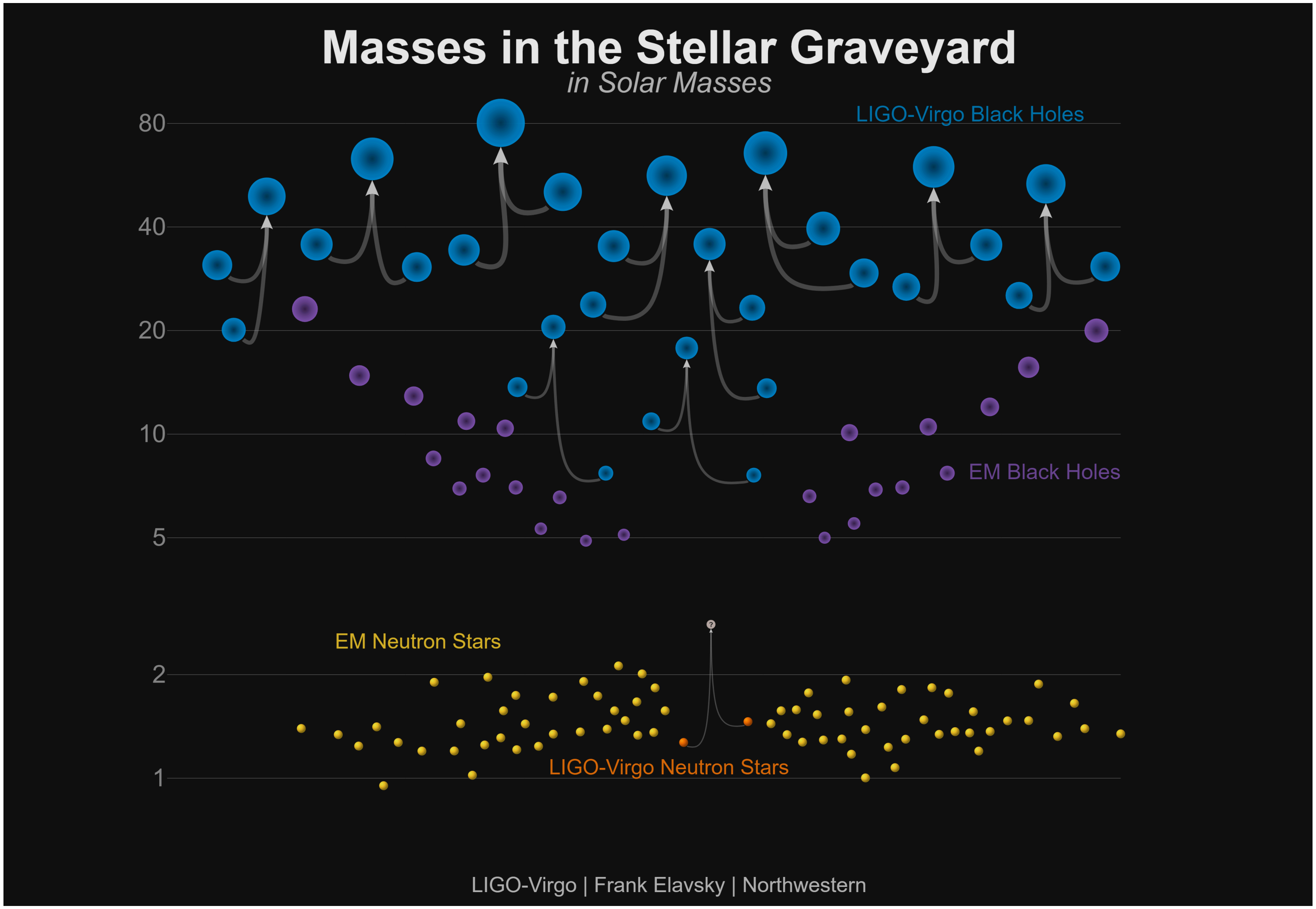


Three BBH events, compared



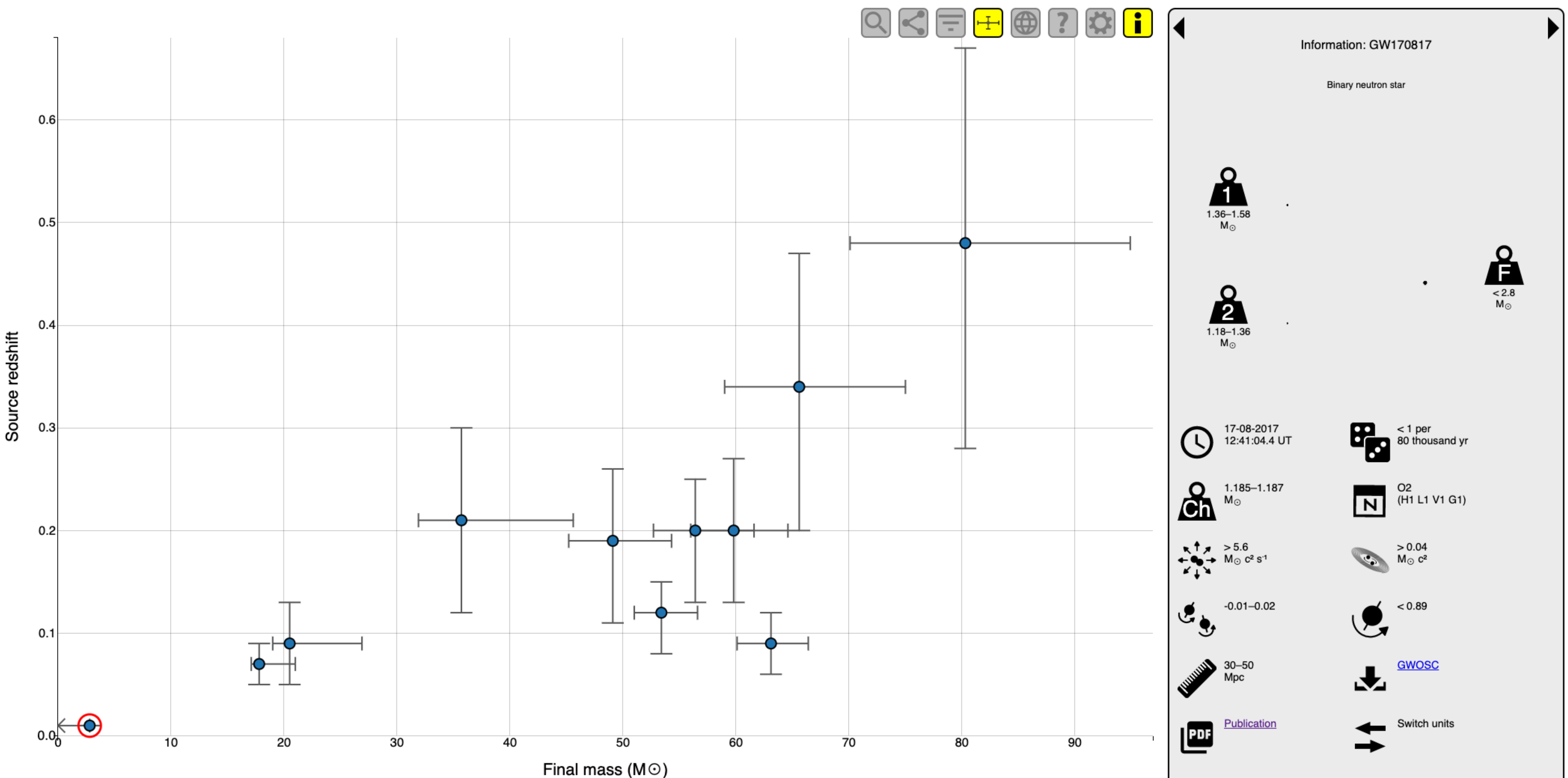
Abbott, et al., LIGO Scientific Collaboration and Virgo Collaboration, “Binary Black Hole Mergers in the first Advanced LIGO Observing Run”, https://arxiv.org/abs/1606.04856, Phys. Rev. X 6, 041015 (2016)

Starting to build up a mass distribution



http://ligo.org/detections/GW170814.php ; https://media.ligo.northwestern.edu/gallery/mass-plot

LIGO-Virgo Compact Binary Catalogue



http://catalog.cardiffgravity.org/

Data release:

https://www.gw-openscience.org/catalog/

- GWTC-1 strain data, parameter estimation samples, skymaps, …
- Full O1 & O2 strain data
- Tutorial, software
- Detector status
- Event alerts
- Lots more!

Gravitational Wave Open Science Center

Data ▾ Software ▾ Online Status ▾ About GWOSC ▾

Catalog GWTC-1-confident

Confident detections from GWTC-1, the Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs.

Catalog Description

For strain data:
- Click an event name
- Or see the JSON file list.

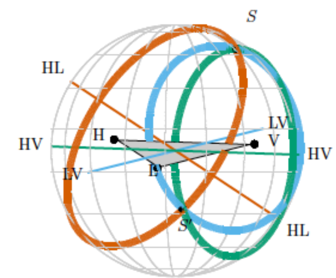
JSON Parameter Table

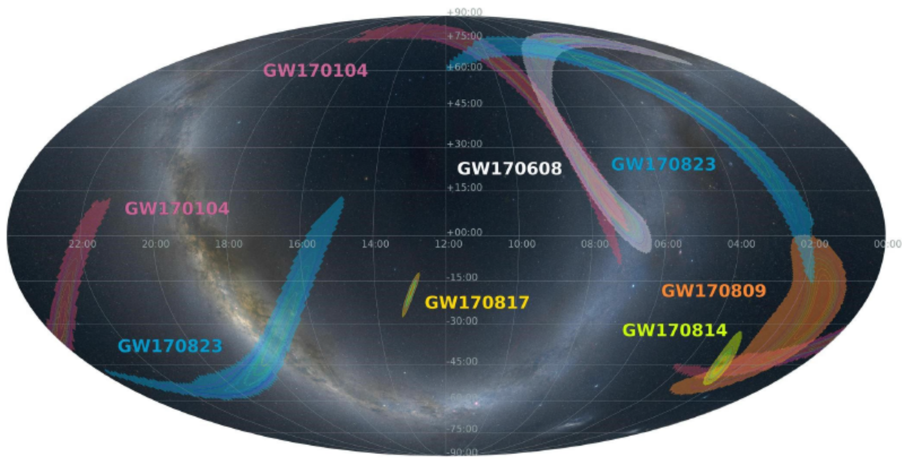
Show/hide columns

SORT: EVENT (A-Z)

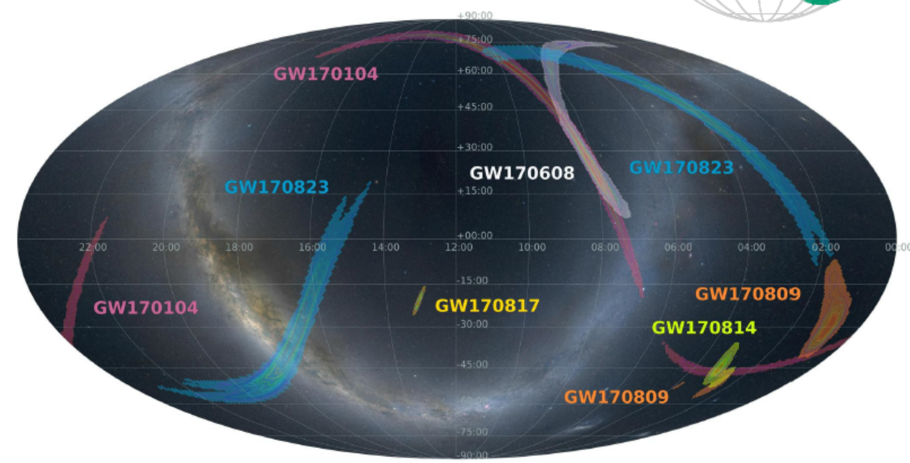
Event	Primary mass (M_sun)	Secondary mass (M_sun)	Effective inspiral spin	chirp mass (M_sun)	Final spin	Final mass (M_sun)	Luminosity distance (Mpc)	GPS time (s)
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$-0.01^{+0.12}_{-0.13}$	$28.6^{+1.6}_{-1.5}$	$0.69^{+0.05}_{-0.04}$	$63.1^{+3.3}_{-3.0}$	430^{+150}_{-170}	1126259462.4
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$0.04^{+0.28}_{-0.19}$	$15.2^{+2.0}_{-1.1}$	$0.67^{+0.13}_{-0.11}$	$35.7^{+9.9}_{-3.8}$	1060^{+540}_{-480}	1128678900.4
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$0.18^{+0.20}_{-0.12}$	$8.9^{+0.3}_{-0.3}$	$0.74^{+0.07}_{-0.05}$	$20.5^{+6.4}_{-1.5}$	440^{+180}_{-190}	1135136350.6
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$-0.04^{+0.17}_{-0.20}$	$21.5^{+2.1}_{-1.7}$	$0.66^{+0.08}_{-0.10}$	$49.1^{+5.2}_{-3.9}$	960^{+430}_{-410}	1167559936.6
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$0.03^{+0.19}_{-0.07}$	$7.9^{+0.2}_{-0.2}$	$0.69^{+0.04}_{-0.04}$	$17.8^{+3.2}_{-0.7}$	320^{+120}_{-110}	1180922494.5
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$0.36^{+0.21}_{-0.25}$	$35.7^{+6.5}_{-4.7}$	$0.81^{+0.07}_{-0.13}$	$80.3^{+14.6}_{-10.2}$	2750^{+1350}_{-1320}	1185389807.3
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$0.07^{+0.16}_{-0.16}$	$25.0^{+2.1}_{-1.6}$	$0.70^{+0.08}_{-0.09}$	$56.4^{+5.2}_{-3.7}$	990^{+320}_{-380}	1186302519.8
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$0.07^{+0.12}_{-0.11}$	$24.2^{+1.4}_{-1.1}$	$0.72^{+0.07}_{-0.05}$	$53.4^{+3.2}_{-2.4}$	580^{+160}_{-210}	1186741861.5
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$0.00^{+0.02}_{-0.01}$	$1.186^{+0.001}_{-0.001}$	≤ 0.89	≤ 2.8	40^{+10}_{-10}	1187008882.4
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$-0.09^{+0.18}_{-0.21}$	$26.7^{+2.1}_{-1.7}$	$0.67^{+0.07}_{-0.08}$	$59.8^{+4.8}_{-3.8}$	1020^{+430}_{-360}	1187058327.1
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$0.08^{+0.20}_{-0.22}$	$29.3^{+4.2}_{-3.2}$	$0.71^{+0.08}_{-0.10}$	$65.6^{+9.4}_{-6.6}$	1850^{+840}_{-840}	1187529256.5

Sky localization for O2 detected events





Distributed **low-latency** O2 skymaps in ICRS coordinates - Mollweide projection.
Shaded areas: 90% CR of source localization.
BAYESTAR (Singer & Price 2016)

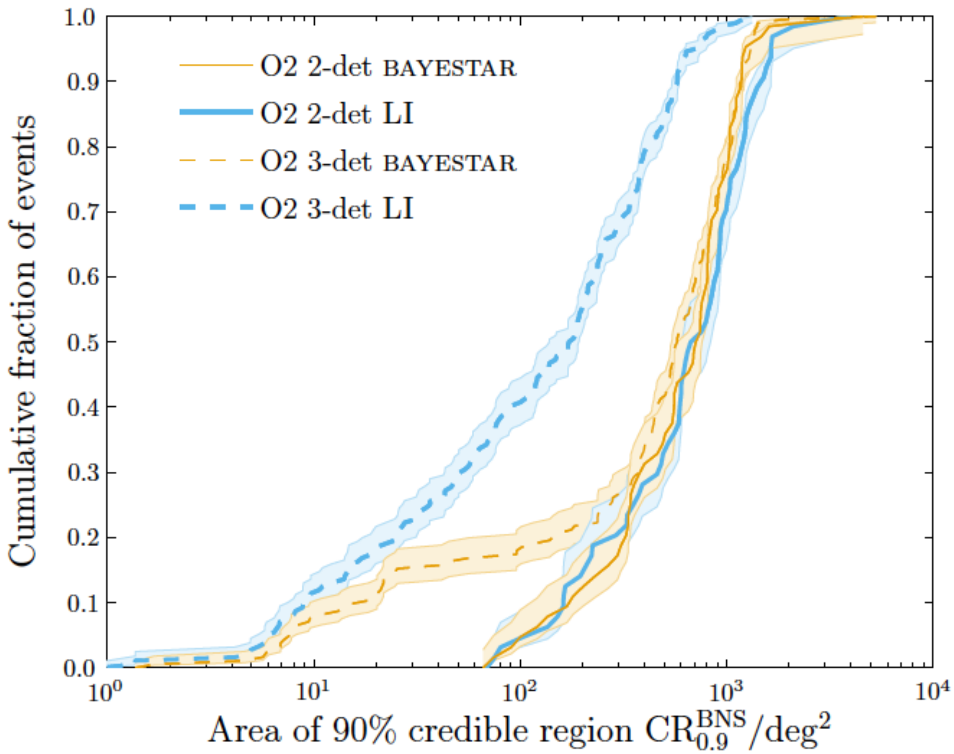


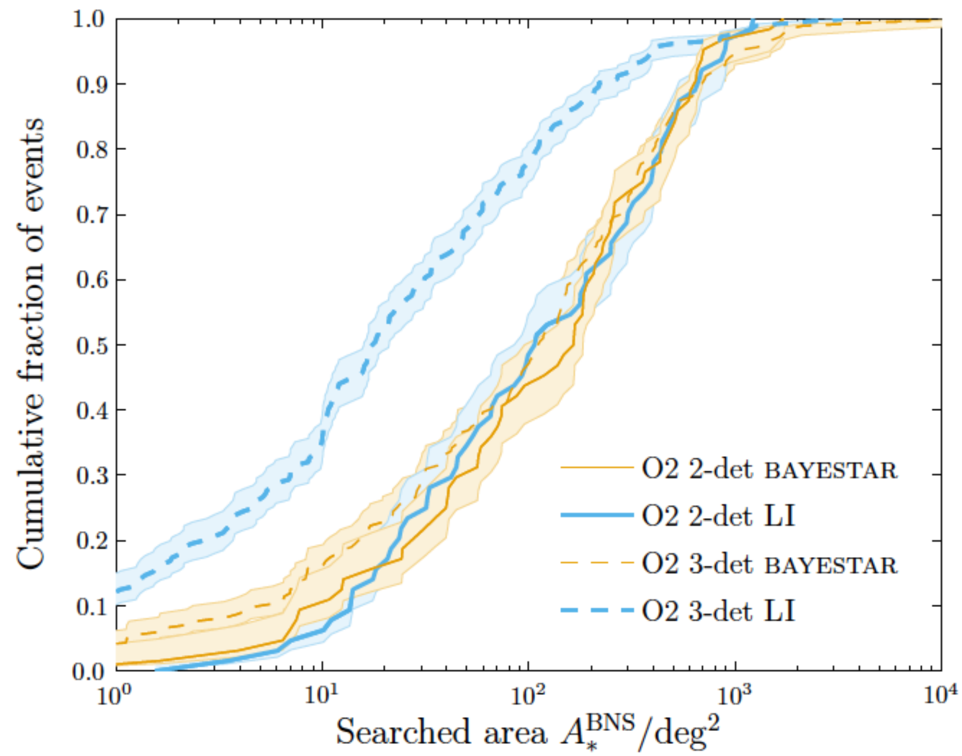
Offline O2 skymaps from GWTC-1.
lalInference (Veitch et al. 2015)

- Inclusion of Virgo greatly improves sky localization: importance of a *global GW detector network* for accurate localization of GW sources (GW170814, GW170817, GW170818)
- GW170818 (LHV) is best localized BBH to date: with a 90% area of 39 deg^2

Low-Latency Gravitational Wave Alerts - Astrophys. J. 875, 161 (2019)
GWTC-1 - arxiv.org/abs/1811.12907 (2018)

Sky localization in O2





$CR^{BNS}_{0.9}$, the (smallest) area enclosing 90% of the total posterior probability.

A^{BNS}_{*}, the area of the smallest credible region containing the true position.

Abbott, B.P et al. Living Rev Relativity (2018) 21: 3. https://doi.org/10.1007/s41114-018-0012-9

GraceDB — Gravitational-Wave Candidate Event Database

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Superevent Info

Superevent ID	Category	Labels	FAR (Hz)	FAR (yr^{-1})	t_start	t_0	t_end	UTC Submission time	Links
S190701ah	Production	PE_READY ADVOK SKYMAP_READY EMBRIGHT_READY PASTRO_READY DQOK GCN_PRELIM_SENT	1.916e-08	1 per 1.6543 years	1246048403.576563	1246048404.577637	1246048405.814941	2019-07-01 20:33:24 UTC	Data

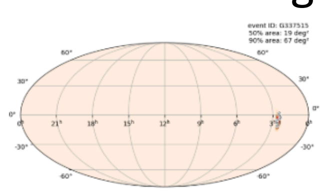
Preferred Event Info

Group	Pipeline	Search	Instruments	GPS Time Event time	UTC Submission time
CBC	pycbc	AllSky	H1,L1,V1	1246048404.5776	2019-07-01 20:33:45 UTC

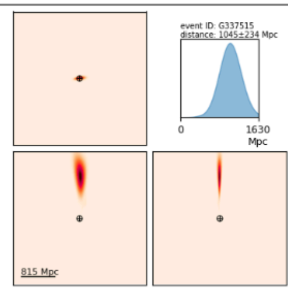
Superevent Log Messages

Sky Localization

90% area: 67 deg^2

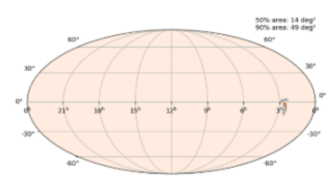


Mollweide projection of bayestar.fits.gz bayestar.png. Submitted by LIGO/Virgo EM Follow-Up on Jul 1, 2019 20:37:46 UTC

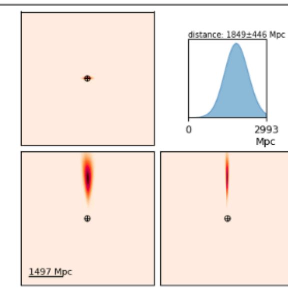


Volume rendering of bayestar.fits.gz bayestar.volume.png. Submitted by LIGO/Virgo EM Follow-Up on Jul 1, 2019 20:39:48 UTC

90% area: 49 deg^2

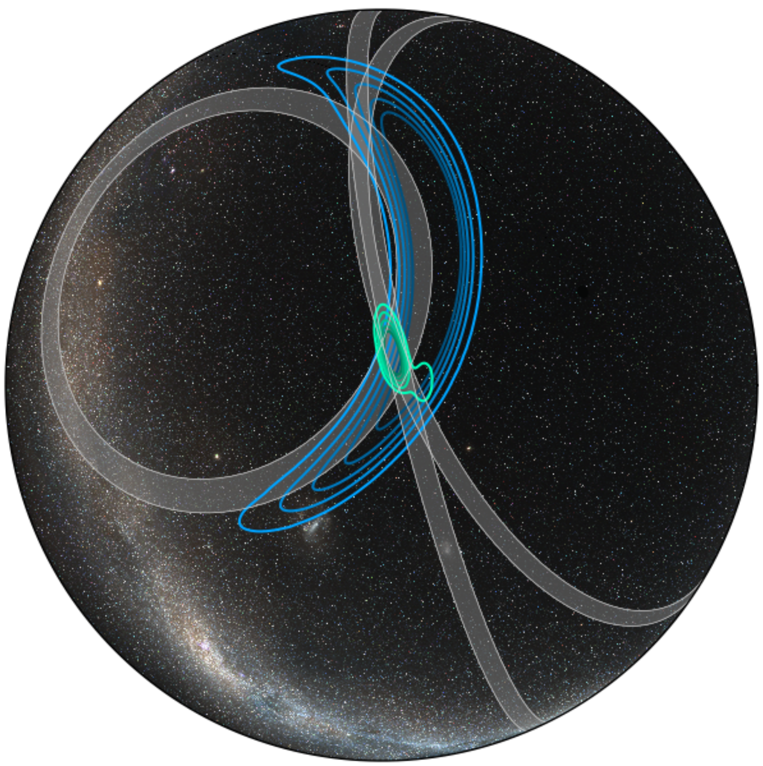


Mollweide projection of LALInference.offline.fits.gz LALInference.offline.png. Submitted by LIGO/Virgo EM Follow-Up on Jul 5, 2019 16:09:52 UTC

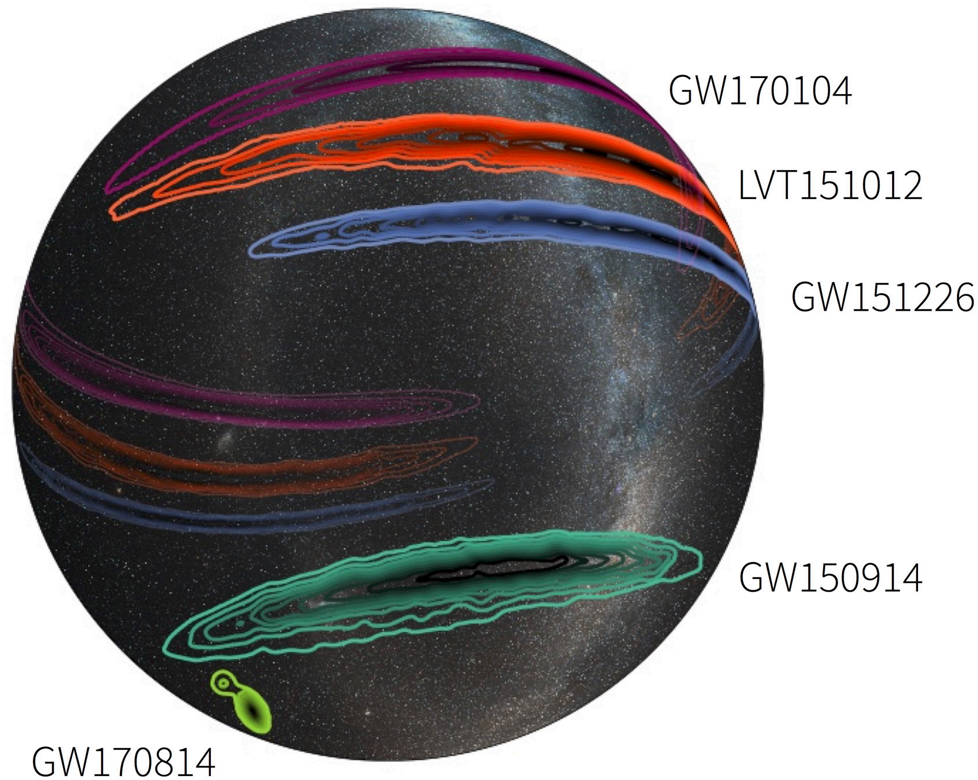


Volume rendering of LALInference.offline.fits.gz LALInference.offline.volume.png. Submitted by LIGO/Virgo EM Follow-Up on Jul 5, 2019 16:10:57 UTC

Greatly improved sky localization with 3 detectors



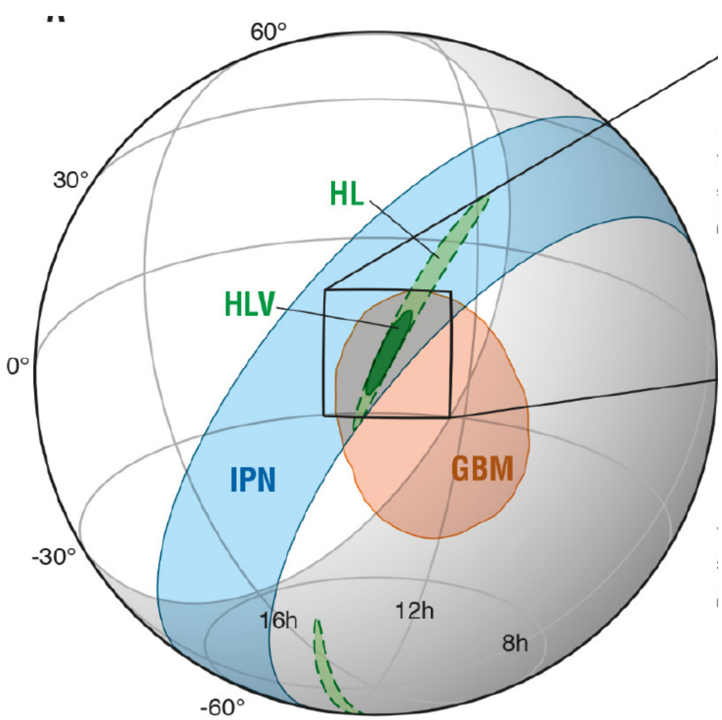
Credit: LIGO/Virgo/NASA/Leo Singer (Milky Way image: Axel Mellinger)



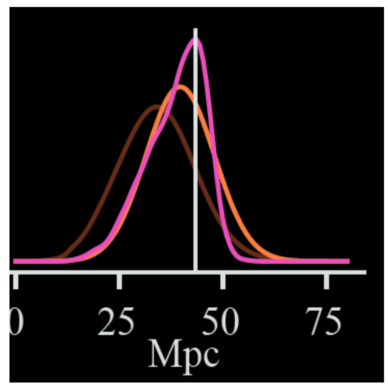
http://ligo.org/detections/GW170814.php

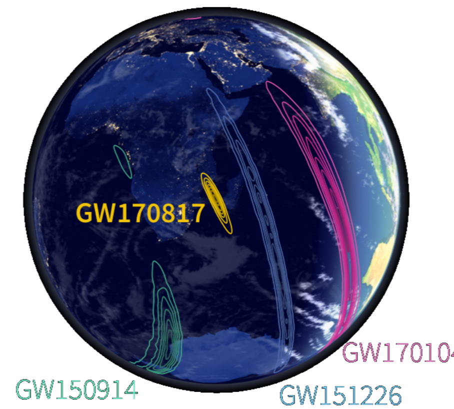
Localization of GW170817

Source located to 28 sq deg, and ~ 40 Mpc.
Time is of the essence!
(Initial alert sent out *27 minutes* after the GWs passed through LIGO)

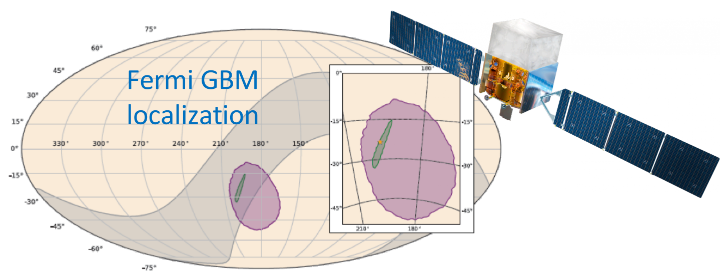


We can locate the source in 3D
– GWs are "standard sirens"



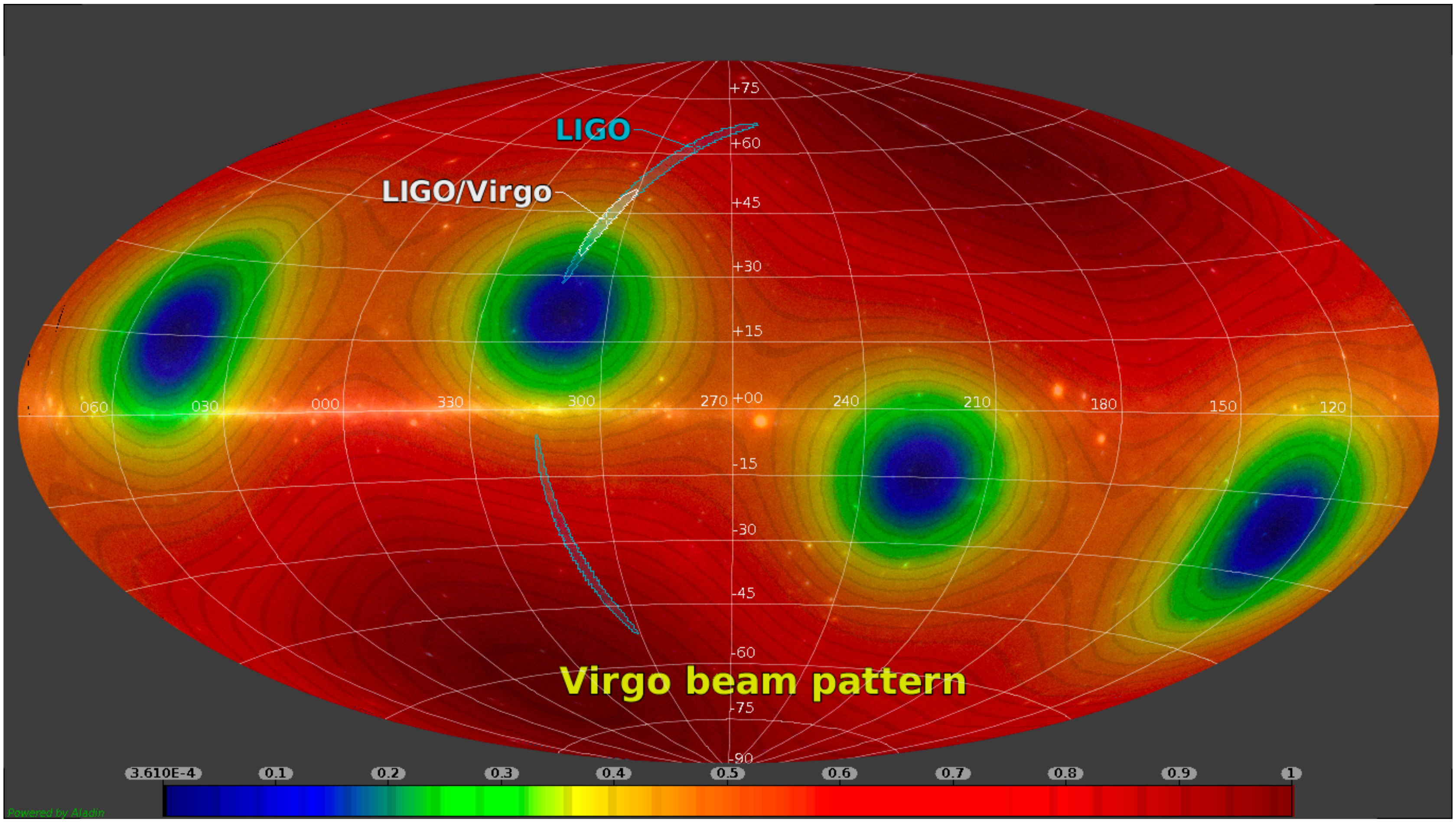


Credit: LIGO/Virgo/NASA/Leo Singer



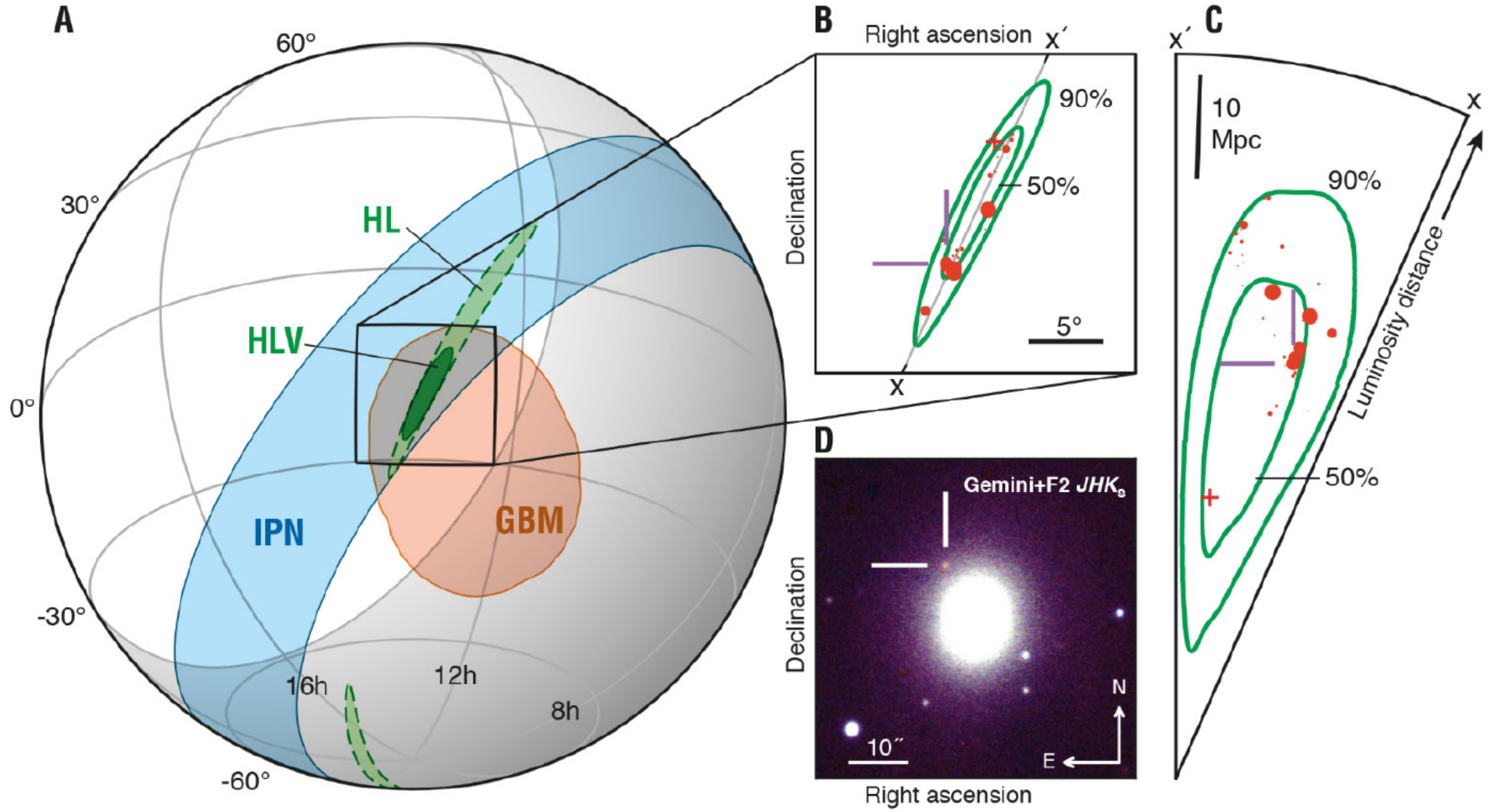
Virgo "non-detection" of GW170817 was very important for sky localization!

The signal was in Virgo's "blind spot".
Reduces the localization patch to "only" ~28 deg^2



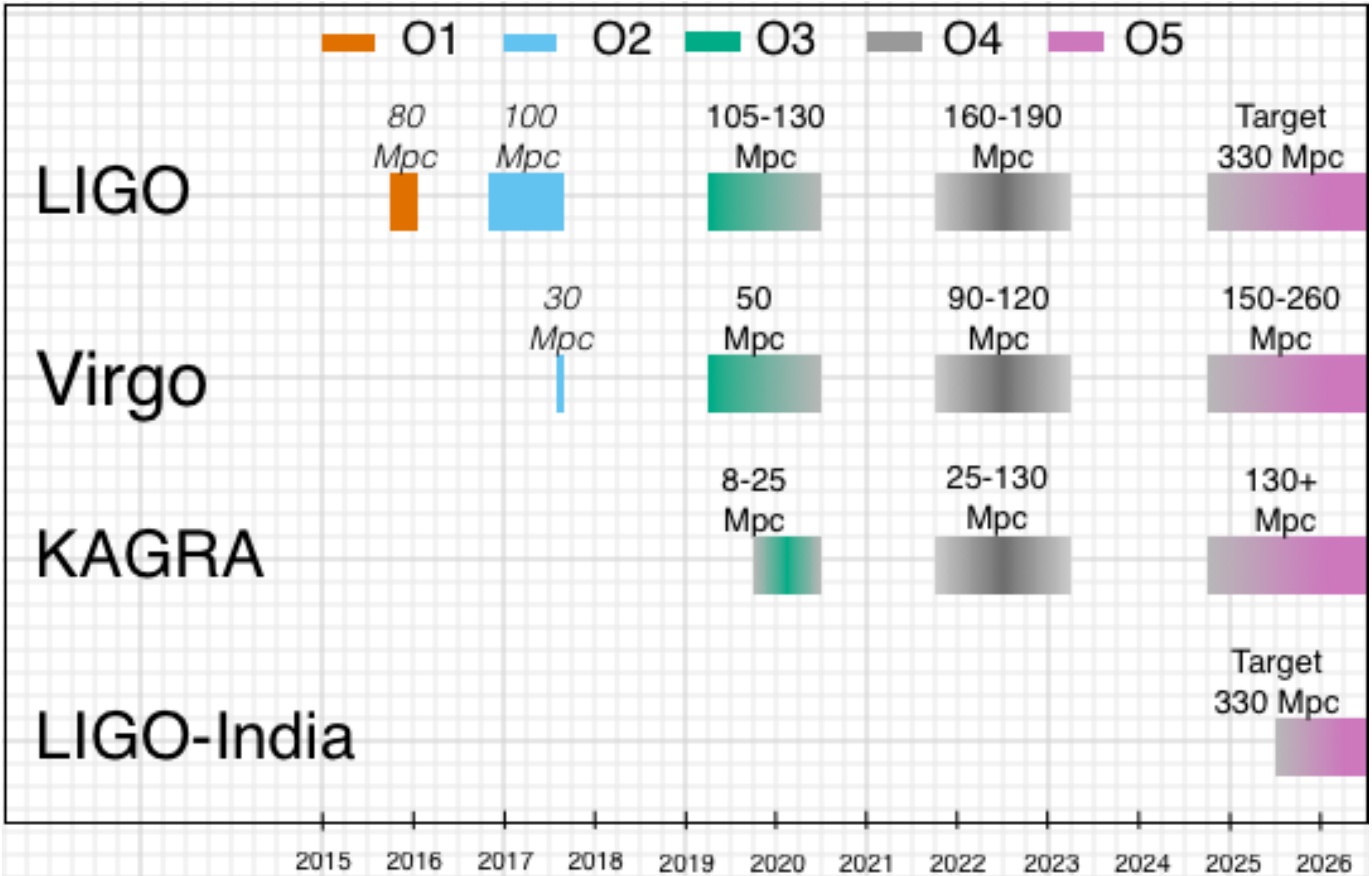
LIGO-Virgo / Greco, Arnaud, Vicere (2017). Background: Fermi/NASA

GW170817 - The next evening



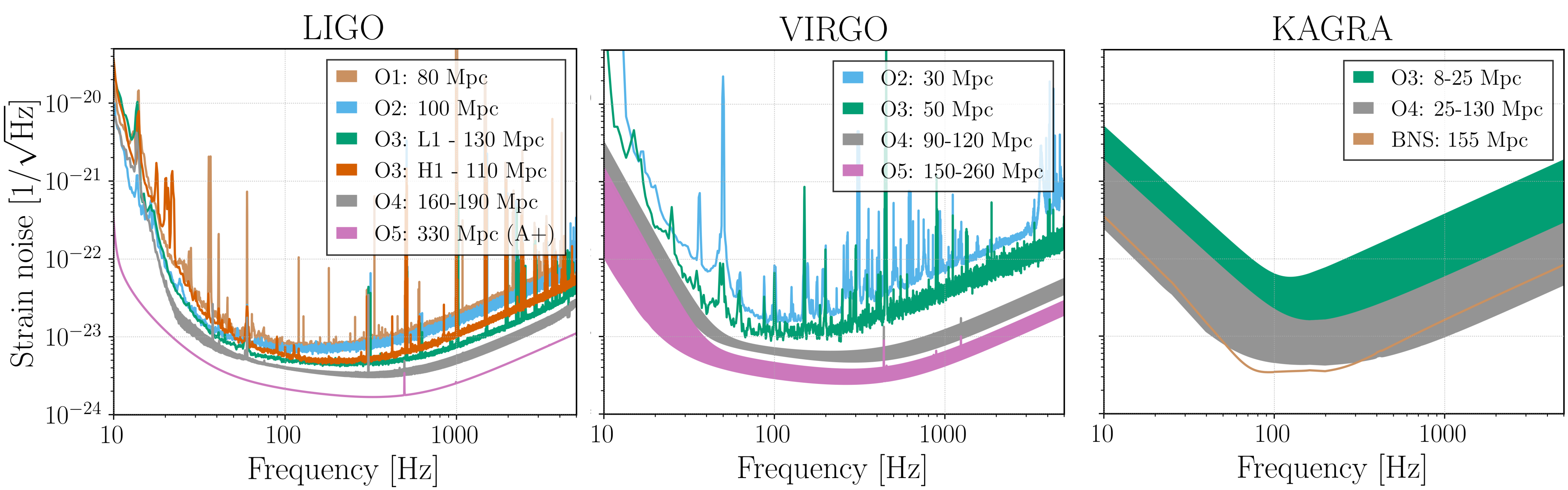
M. M. Kasliwal *et al.*, *Science* 10.1126/science.aap9455 (2017).

Coordinated Observations with the GW Network



https://dcc.ligo.org/LIGO-P1900218/public - pending update to: Abbott, B.P et al. Living Rev Relativ (2018) 21: 3.

Estimated Sensitivity Evolution: LIGO, Virgo, KAGRA



LIGO **Virgo** **KAGRA**

https://dcc.ligo.org/LIGO-P1900218/public - pending update to: Abbott, B.P et al. Living Rev Relativ (2018) 21: 3.

Estimated Inspiral Ranges for LIGO, Virgo, KAGRA

'Seeing' distance (averaged over all sky and binary orientations) to binary neutron star (1.4 $M_\odot$-1.4 $M_\odot$) and binary black hole (30 $M_\odot$-30 $M_\odot$) for SNR = 8

		O1	O2	O3	O4	O5
BNS Range (Mpc)	aLIGO	80	100	110 – 130	160 – 190	330
	AdV	–	30	50	90 – 120	150 – 260
	KAGRA	–	–	8 – 25	25 – 130	130+
BBH Range (Mpc)	aLIGO	740	910	990 – 1200	1400 – 1600	2500
	AdV	-	270	500	860 – 1100	1300 – 2100
	KAGRA	-	-	80 – 260	260 – 1200	1200+
NSBH Range (Mpc)	aLIGO	140	180	190 – 240	300 – 330	590
	AdV	-	50	90	170 – 220	270 – 480
	KAGRA	-	-	15 – 45	45 – 290	290+
Burst Range (Mpc)	aLIGO	50	60	80 – 90	110 – 120	210
	AdV	-	25	35	65 – 80	100 – 155
	KAGRA	-	-	5 – 25	25 – 95	95+

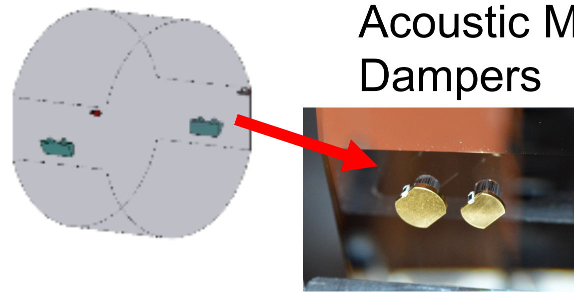
Note: Horizon distance ≈ 2.25 x average distance

https://dcc.ligo.org/LIGO-P1900218/public - pending update to: Abbott, B.P et al. Living Rev Relativ (2018) 21: 3.

Major LIGO Detector Improvements for O3

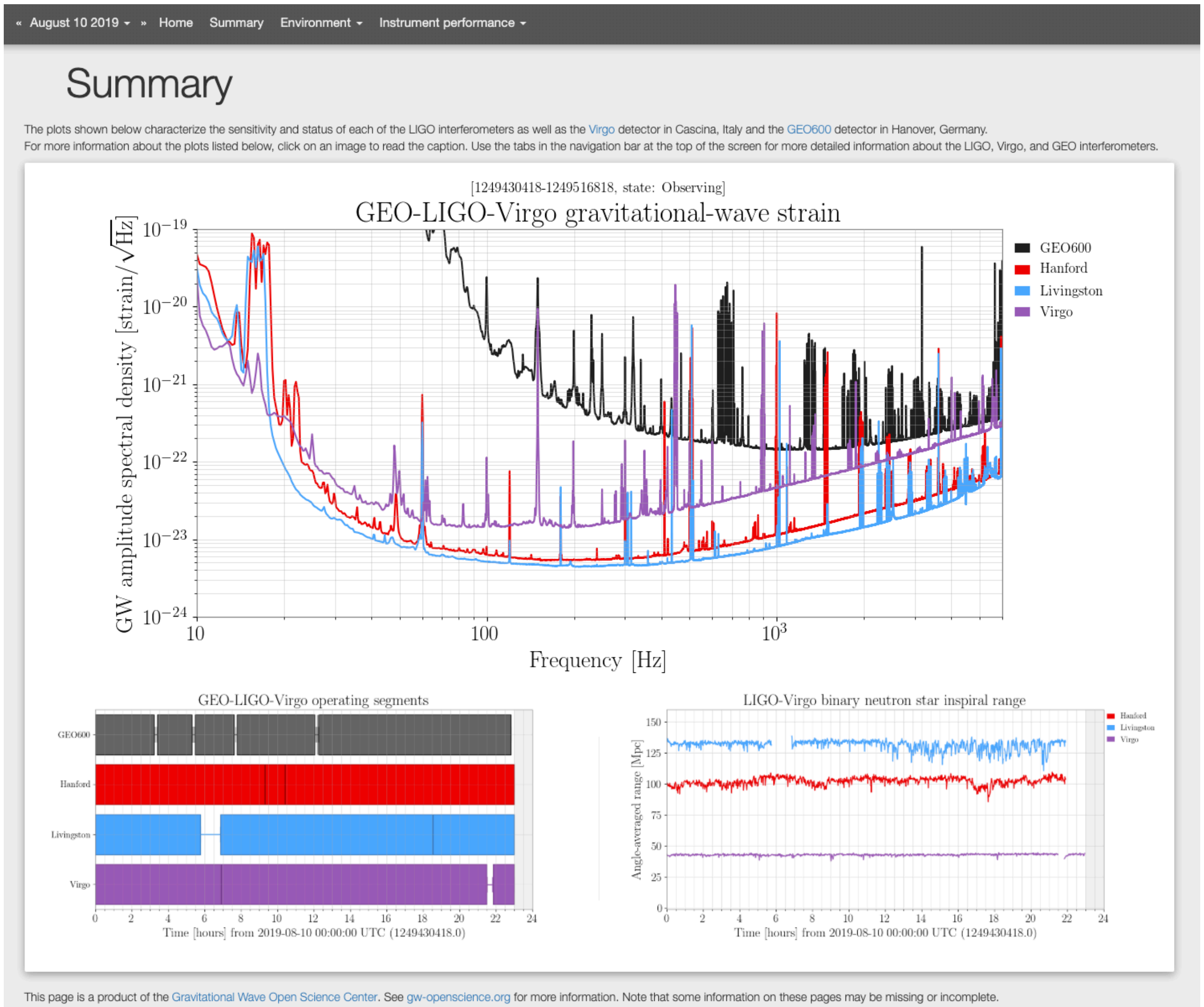
- Squeezed light injection
  - Goal is 3 dB noise reduction; have seen 2+ dB
- Replaced all end test masses, added annular end reaction masses
- Vastly improved interferometer stray light control
- New robust 70W laser amplifiers → 50 W into interferometers
- Installation of acoustic mass dampers on all test masses
  - Parametric instability suppression → hasn't been a problem in O3, shouldn't be a problem for O4!
- New monolithic Signal Recycling Cavity mirrors, new 118 MHz SRC modulation sideband control scheme
- Replace Output Faraday Isolators
- Electric field meters installed in one end station for H1 and L1

Acoustic Mass Dampers



LIGO Progress – Online detector status

https://www.gw-openscience.org/detector_status/



Gravitational Wave Detector Network

Operational Snapshot as of Aug 11, 01:14 UTC

Detector	Status	Duration
GEO 600	Observing	12:53
LIGO Hanford	Observing	14:48
LIGO Livingston	Observing	6:40
Virgo	Science	3:23
KAGRA	Future addition	

Detector status summary pages

LVC links

https://gracedb.ligo.org/superevents/public/O3/

GraceDB — Gravitational-Wave Candidate Event Database

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LIGO/Virgo Public Alerts

Detection candidates: 22

SORT: EVENT ID (A-Z) ▼

Event ID	Possible Source (Probability)	UTC	GCN	Location	FAR	Comments
S190808ae	Terrestrial (57%), BNS (43%)	Aug. 8, 2019 22:21:21 UTC	GCN Circulars Notices | VOE		1.0622 per year	RETRACTED
S190728q	BBH (95%), MassGap (5%)	July 28, 2019 06:45:10 UTC	GCN Circulars Notices | VOE		1 per 1.2541e+15 years	
S190727h	BBH (92%), Terrestrial (5%), MassGap (3%)	July 27, 2019 06:03:33 UTC	GCN Circulars Notices | VOE		1 per 229.92 years	
S190720a	BBH (99%), Terrestrial (1%)	July 20, 2019 00:08:36 UTC	GCN Circulars Notices | VOE		1 per 8.3367 years	
S190718y	Terrestrial (98%), BNS (2%)	July 18, 2019 14:35:12 UTC	GCN Circulars Notices | VOE		1.1514 per year	
S190707q	BBH (>99%)	July 7, 2019 09:33:26 UTC	GCN Circulars Notices | VOE		1 per 6018.9 years	
S190706ai	BBH (99%), Terrestrial (1%)	July 6, 2019 22:26:41 UTC	GCN Circulars Notices | VOE		1 per 16.673 years	
S190701ah	BBH (93%), Terrestrial (7%)	July 1, 2019 20:33:06 UTC	GCN Circulars Notices | VOE		1 per 1.6543 years	
S190630ag	BBH (94%), MassGap (5%)	June 30, 2019 18:52:05 UTC	GCN Circulars Notices | VOE		1 per 2.2077e+05 years	
S190602aq	BBH (99%)	June 2, 2019 17:59:27 UTC	GCN Circulars Notices | VOE		1 per 16.673 years	
S190524q	Terrestrial (71%), BNS (29%)	May 24, 2019 04:52:06 UTC	GCN Circulars Notices | VOE		1 per 4.5458 years	RETRACTED
S190521r	BBH (>99%)	May 21, 2019 07:43:59 UTC	GCN Circulars Notices | VOE		1 per 100.04 years	
S190521g	BBH (97%), Terrestrial (3%)	May 21, 2019 03:02:29 UTC	GCN Circulars Notices | VOE		1 per 8.3367 years	
S190519bj	BBH (96%), Terrestrial (4%)	May 19, 2019 15:35:44 UTC	GCN Circulars Notices | VOE		1 per 5.5578 years	
S190518bb	BNS (75%), Terrestrial (25%)	May 18, 2019 19:19:19 UTC	GCN Circulars Notices | VOE		1 per 3.1557 years	RETRACTED
S190517h	BBH (98%), MassGap (2%)	May 17, 2019 05:51:01 UTC	GCN Circulars Notices | VOE		1 per 13.354 years	
S190513bm	BBH (94%), MassGap (5%)	May 13, 2019 20:54:28 UTC	GCN Circulars Notices | VOE		1 per 84864 years	
S190512at	BBH (99%), Terrestrial (1%)	May 12, 2019 18:07:14 UTC	GCN Circulars Notices | VOE		1 per 16.673 years	
S190510g	Terrestrial (58%), BNS (42%)	May 10, 2019 02:59:39 UTC	GCN Circulars Notices | VOE		1 per 3.5872 years	
S190503bf	BBH (96%), MassGap (3%)	May 3, 2019 18:54:04 UTC	GCN Circulars Notices | VOE		1 per 19.368 years	
S190426c	BNS (49%), MassGap (24%), Terrestrial (14%), NSBH (13%)	April 26, 2019 15:21:55 UTC	GCN Circulars Notices | VOE		1 per 1.6276 years	
S190425z	BNS (>99%)	April 25, 2019 08:18:05 UTC	GCN Circulars Notices | VOE		1 per 69834 years	
S190421ar	BBH (97%), Terrestrial (3%)	April 21, 2019 21:38:56 UTC	GCN Circulars Notices | VOE		1 per 2.1285 years	

GCN/LVC Notices and Circulars

- Preliminary Notices sent out within ~ minutes with no human intervention.

https://gcn.gsfc.nasa.gov/selected.html

Collected Information About Recent GRBs/GW_events/SGRs/Transients

1. Recent GRBs/GW_event/SGRs/Transients
2. Past GRBs/GW_event/SGRs/Transients (2017-1997)
3. Circular-by-Circular in serial number sequence

This page contains links to files of all the Circulars on the given GRB/GW_event/transient.
This includes the circulars published by the mission-instrument(s) making a detection,
and by the follow-up observers.

For each GRB/transient, the link label contains a series of strings.
These strings show which mission-instrument made the initial detection (the first to publish for simultaneous detections),
then zero or more strings showing which other mission-instruments made detections (in the order published), and
the "Optical" string if there were any ground-based optical detection(s) (or "optical" if only upper limit(s)),
"Radio" for a detection or "radio" for an upper limit observation(s), and
"z=n.nnn" for a redshift measurement.

Since this page and the linked pages herein are constantly changing, you should hit the RELOAD button every time you view it.

If there is no link to a recent burst, this is because the addition of the explicit link is done manually.
However, the file that the would-be link would point to IS created automatically. So, with a small effort
the savy web surfer can get to the file without having a formal link by just editing one of the other links
(shown in your 'location URL window' in your browser) to contain the new new burst date
(ie change the old 'yymmdd' field in the URL to the new burst's 'yymmdd'
(with an 'A' or 'B' etc suffix change as well) and hit reload -- note it is prefix-dependant: 'GRB', 'S', 'icecube_').
This 30-sec effort will get you to the recent burst's concatenated-file of all Circulars,
even before a slow human (such as myself) comes along to add the explicit link in this page.

Recent GRBs/SGRs/XRFs/Transients:

LIGO/Virgo S190808ae: GCN Circ archive: MASTER, LIGO/Virgo, IceCube, HAWC

HAWC-190806A: GCN Circ archive: MASTER, HAWC, IceCube

GRB 190805B: GCN Circ archive: Fermi-GBM, MAXI, BALROG

GRB 190805A: GCN Circ archive: Fermi-GBM

GRB 190804C: GCN Circ archive: Fermi-GBM, BALROG

GRB 190804B: GCN Circ archive: MAXI, Swift-XRT

GRB 190804A: GCN Circ archive: Fermi-GBM, MASTER

GRB 190731A: GCN Circ archive: Fermi-GBM/-LAT, Swift, CALET, Fermi-GBM, IPN, Swift-XRT, optical, Swift-UVOT, AstroSat CZTI

IceCube-190730A: GCN Circ archive: IceCube, MASTER, INTEGRAL SPI-ACS, Fermi-GBM, HAWC, Fermi-LAT, IceCube status

LIGO/Virgo S190728q: GCN Circ archive: MASTER, IceCube, LIGO/Virgo, MAXI/GSC, SPI-ACS/INTEGRAL, INTEGRAL SPI-ACS, HAWC, AGILE-MCAL, ANTARES, AGILE-GRID, Fermi-GBM

GRB 190727B: GCN Circ archive: Swift-BAT, Fermi-GBM, BALROG, Fermi-LAT, KONUS-Wind

GRB 190727A: GCN Circ archive: Fermi-GBM, BALROG

LIGO/Virgo S190727h: GCN Circ archive: IceCube, optical, LIGO/Virgo, MAXI/GSC, INTEGRAL-SPI-ACS, AGILE-MCAL, ANTARES, HAWC, Fermi-GBM/-LAT, Swift-BAT, LIGO/Virgo status

https://gcn.gsfc.nasa.gov/gcn3/24168.gcn3

```
TITLE:   GCN CIRCULAR
NUMBER:  24168
SUBJECT: LIGO/Virgo S190425z: Identification of a GW compact binary merger candidate
DATE:    19/04/25 09:53:13 GMT
FROM:    Leo Singer at GSFC  <leo.p.singer@nasa.gov>

The LIGO Scientific Collaboration and the Virgo Collaboration report:

We identified the compact binary merger candidate S190425z during
real-time processing of data from LIGO Livingston Observatory (L1) and
Virgo Observatory (V1) at 2019-04-25 08:18:05.017 UTC (GPS time:
1240215503.017). The candidate was found by the GstLAL [1] and PyCBC
Live [2] analysis pipelines.

The signal-to-noise ratio (SNR) was below threshold in V1 so the
candidate was treated as a single-instrument event and no automated
preliminary notice was sent. Nonetheless, the V1 SNR is consistent
with the L1 data given the relative sensitivities of the detectors.
LIGO Hanford Observatory (H1) was offline at the time.

S190425z is an event of interest because its false alarm rate as
estimated by the online analysis is 4.5e-13 Hz, or about one in 7e4
years. The event's properties can be found at this URL:

https://gracedb.ligo.org/superevents/S190425z

The classification of the GW signal, in order of descending
probability, is BNS (>99%), Terrestrial (<1%), NSBH (<1%), BBH (<1%),
or MassGap (<1%).

Assuming the candidate is astrophysical in origin, there is strong
evidence for the lighter compact object having a mass < 3 solar masses
(HasNS: >99%). Using the masses and spins inferred from the signal,
there is strong evidence for matter outside the final compact object
(HasRemnant: >99%).

One skymap is available at this time and can be retrieved from the
GraceDB event page:
 * bayestar.fits.gz, an initial localization generated by BAYESTAR [3],
   distributed via GCN notice about 42 minutes after the candidate.

For the bayestar.fits.gz skymap, the 90% credible region is 10183
deg2. Marginalized over the whole sky, the a posteriori luminosity
distance estimate is 155 +/- 45 Mpc (a posteriori mean +/- standard
deviation). The skymap is coarser than usual due to the low
signal-to-noise ratio in V1; the localization is dominated by the L1
antenna pattern.

For further information about analysis methodology and the contents of
this alert, refer to the LIGO/Virgo Public Alerts User Guide
<https://emfollow.docs.ligo.org/userguide/>.
```


```
 [1] Messick et al. PRD 95, 042001 (2017)
 [2] Nitz et al. PRD 98, 024050 (2018)
 [3] Singer & Price PRD 93, 024013 (2016)
```

https://emfollow.docs.ligo.org/userguide/

LSC LIGO Scientific Collaboration

VIRGO

Public Alerts User Guide

Primer on public alerts for astronomers from the LIGO and Virgo gravitational-wave observatories.

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Question? Issues? Feedback?

Email emfollow-userguide@support.ligo.org

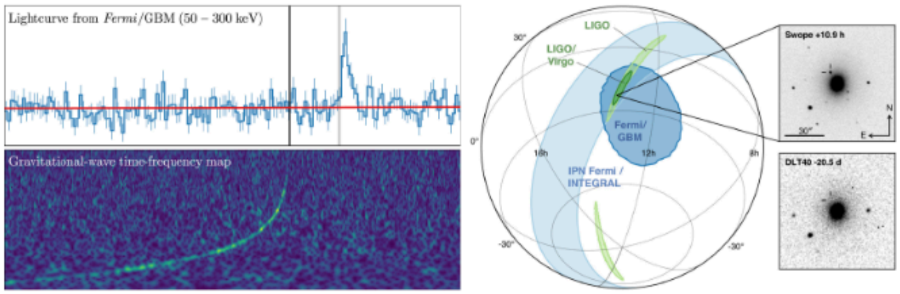
Quick search

Go

National Science Foundation

Getting Started Checklist →

LIGO/Virgo Public Alerts User Guide



Welcome to the LIGO/Virgo Public Alerts User Guide! This document is intended for both professional astronomers and science enthusiasts who are interested in receiving alerts and real-time data products related to gravitational-wave (GW) events.

Three sites (LHO, LLO, Virgo) together form a global network of ground-based GW detectors. The LIGO Scientific Collaboration and the Virgo Collaboration jointly analyze the data in real time to detect and localize transients from compact binary mergers and other sources. When a signal candidate is found, an alert is sent to astronomers in order to search for counterparts (electromagnetic waves or neutrinos).

Advanced LIGO and Advanced Virgo began their third observing run (O3) on April 1, 2019. For the first time, **LIGO/Virgo alerts are public**. Alerts are distributed through NASA's Gamma-ray Coordinates Network (GCN). There are two types of alerts: human-readable GCN Circulars and machine-readable GCN Notices. This document provides a brief overview of the procedures for vetting and sending GW alerts, describes their contents and format, and includes instructions and sample code for receiving GCN Notices and decoding GW sky maps.

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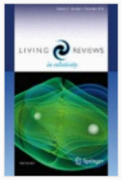


Living Reviews in Relativity
December 2018, 21:3 | Cite as

Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA

Authors | Authors and affiliations

B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, C. Affeldt, M. Agathos, K. Agatsuma, N. Aggarwal, show 1086 more

Abstract

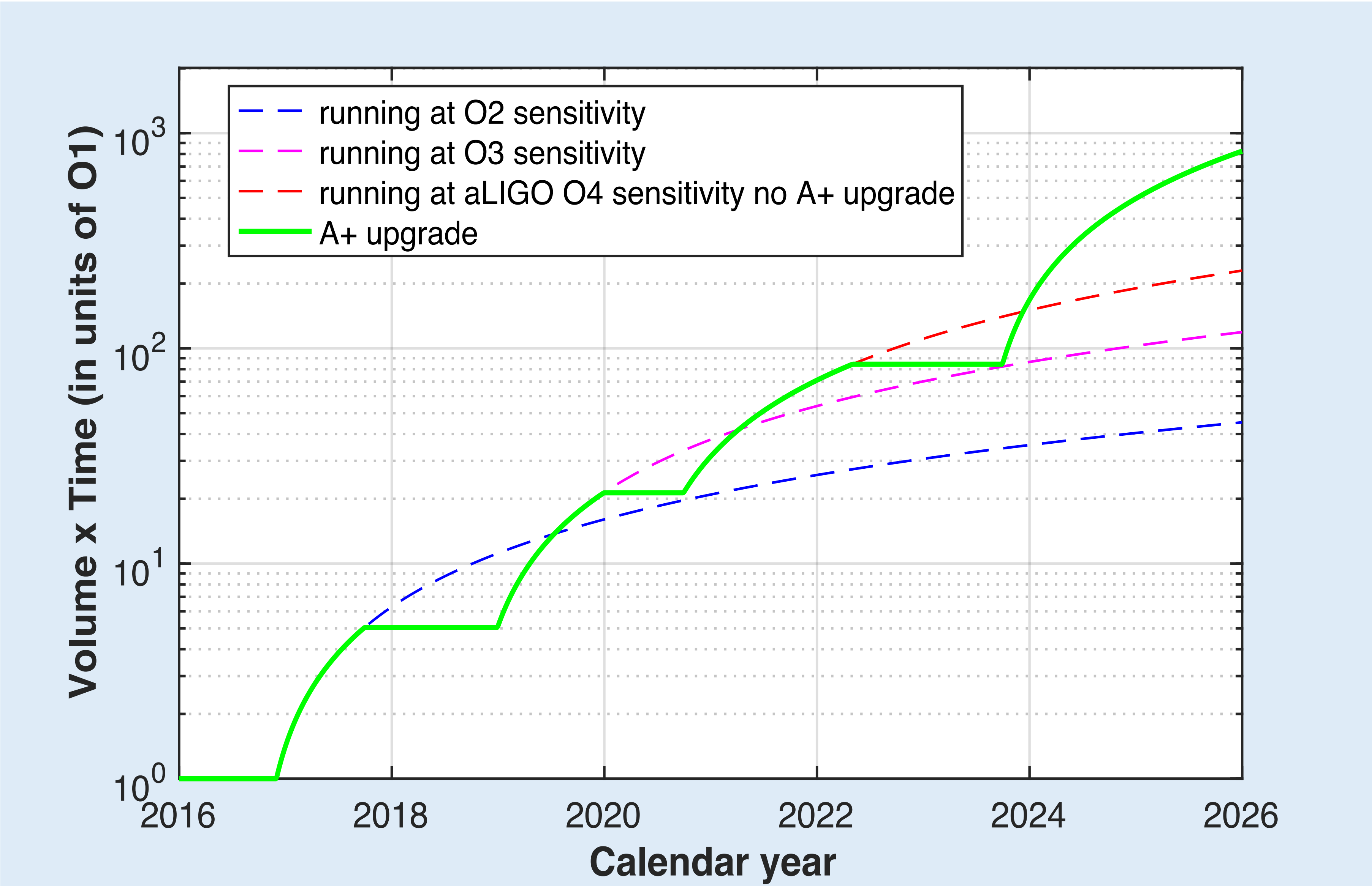
We present possible observing scenarios for the Advanced LIGO, Advanced Virgo and KAGRA gravitational-wave detectors over the next decade, with the intention of providing information to the astronomy community to facilitate planning for multi-messenger astronomy with gravitational waves. We estimate the sensitivity of the network to transient gravitational-wave signals, and study the capability of the network to determine the sky location of the source. We report our findings for gravitational-wave transients, with particular focus on gravitational-wave signals from the inspiral of binary neutron star systems, which are the most promising targets for multi-messenger astronomy. The ability to localize the sources of the detected signals depends on the geographical distribution of the detectors and their relative sensitivity, and 90% credible regions can be as large as thousands of square degrees when only two sensitive detectors are operational. Determining the sky position of a significant fraction of detected signals to areas of 5–20 deg^2 requires at least three detectors of sensitivity within a factor of ~ 2 of each other and with a broad frequency bandwidth. When all detectors, including KAGRA and the third LIGO detector in India, reach design sensitivity, a significant fraction of gravitational-wave signals will be localized to a few square degrees by gravitational-wave observations alone.

Keywords

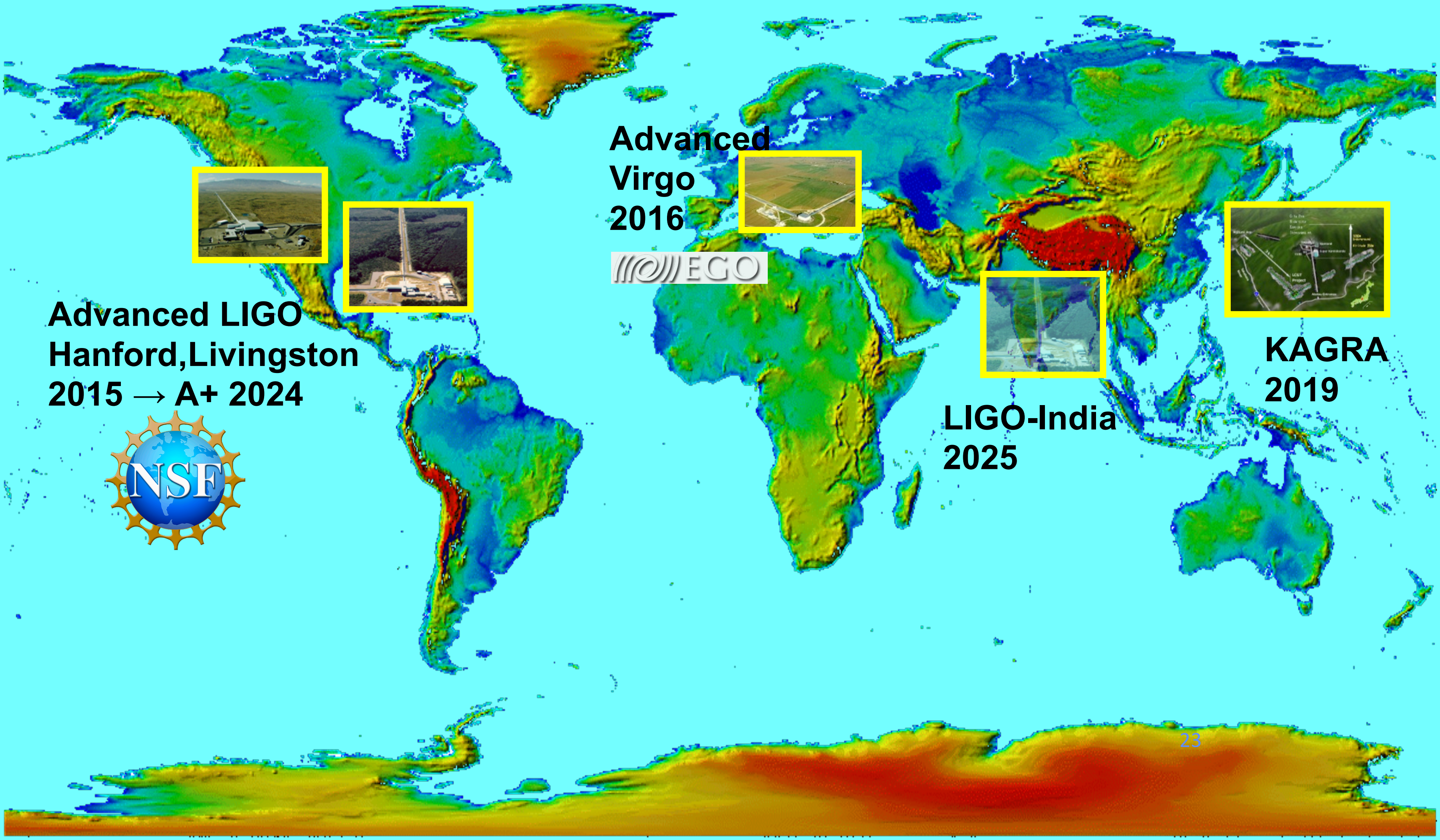
Gravitational waves | Gravitational-wave detectors | Electromagnetic counterparts | Data analysis

Abbott, B.P et al. Living Rev Relativ (2018) 21: 3. https://doi.org/10.1007/s41114-018-0012-9

LIGO in the Era of LSST



The Network in mid-2020's



Advanced LIGO Plus (A+)
A Mid-scale Upgrade to Advanced LIGO

- An incremental upgrade to aLIGO that leverages existing technology and infrastructure,
  with minimal new investment and moderate risk
- Target: factor of 1.7 increase in binary inspiral detection range over aLIGO baseline design

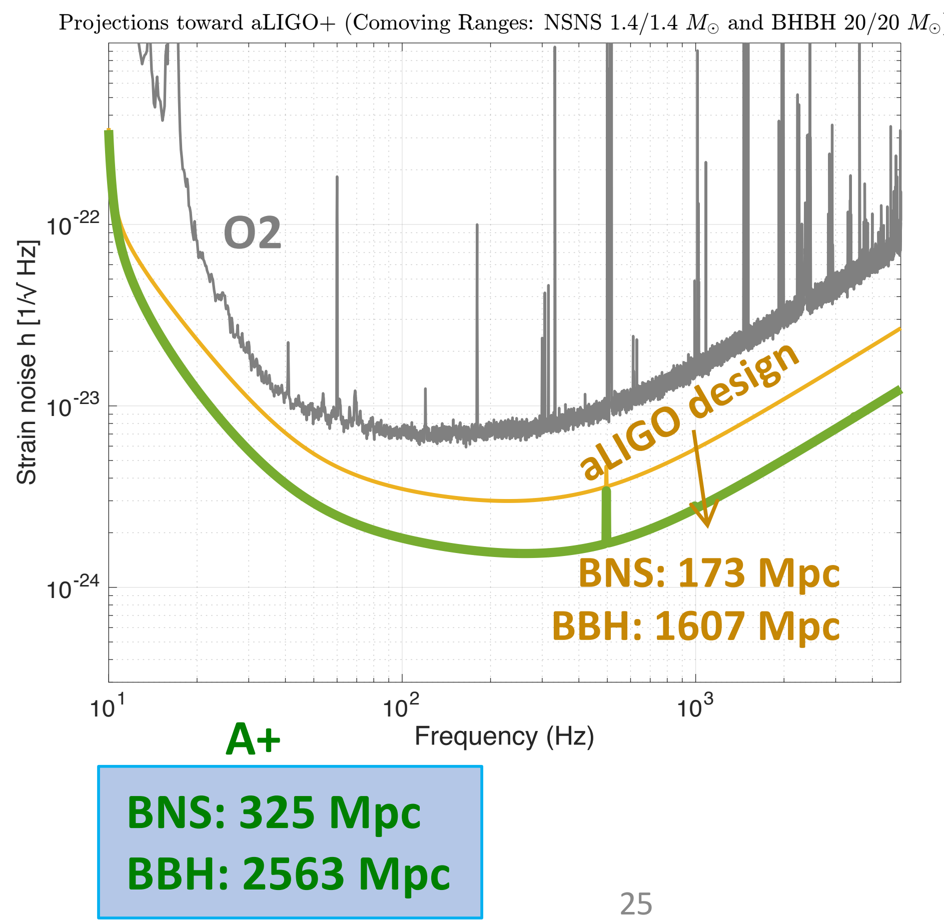
  ➔About a factor of 4-7 greater CBC event rate
- Bridge to future 3G GW astrophysics, cosmology, and nuclear physics
- Stepping stone to 3G detector technology
- Can be observing within 6 years (late 2024)
- "Scientific breakeven" within 1/2 year of operation
- Incremental cost: *a small increment on aLIGO*
  - US$ 20.4M (NSF) + GB£ 10.1M (UKRI/STFC) +AU$ 0.2M (ARC)

Advanced LIGO ‘A+’ ~ 2024/2025 and beyond

- Sensitivity improvement over ALIGO:
  - 1.4/1.4 $M_\odot$ BNS inspiral range by ~ 1.9 to 325 Mpc
  - 30/30 $M_\odot$ binary black hole inspiral range by ~1.6 to > 2.5 Gpc

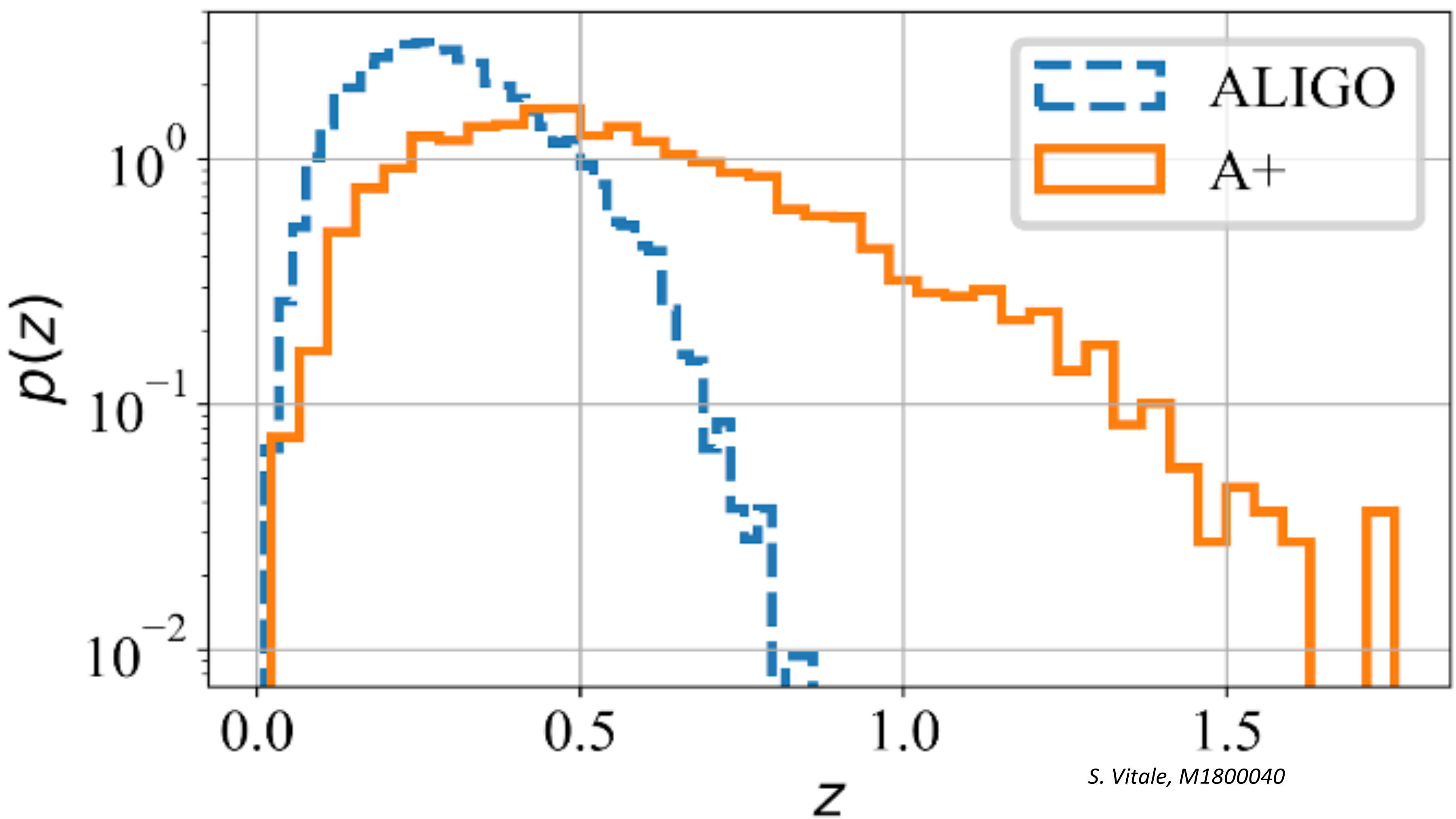
Greater event rate than Advanced LIGO

→Higher SNR CBC events



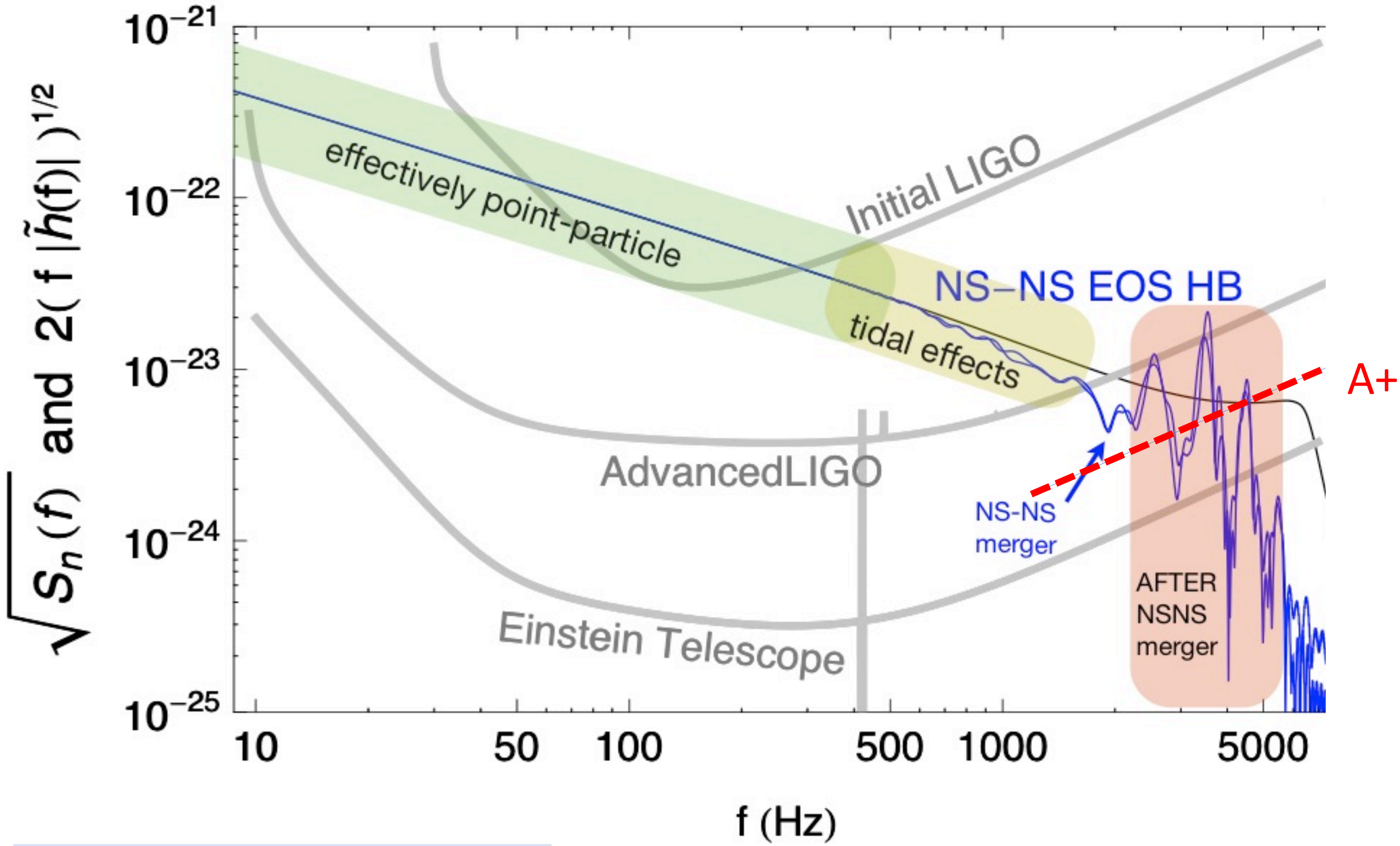
- Employs frequency-dependent squeezing & lower thermal noise mirror coatings
- Currently planning for a 1.5-2 year run duration beginning mid 2024 or early 2025
- ***LIGO-India planned to come online in the A+ configuration in 2025***

BBH redshift distribution
Advanced LIGO → 'A+'   ~ 2024/2025



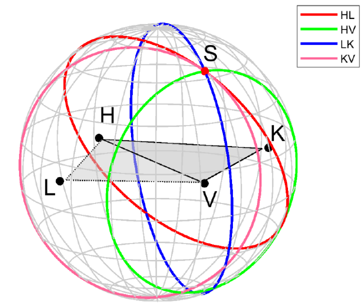
S. Vitale, M1800040

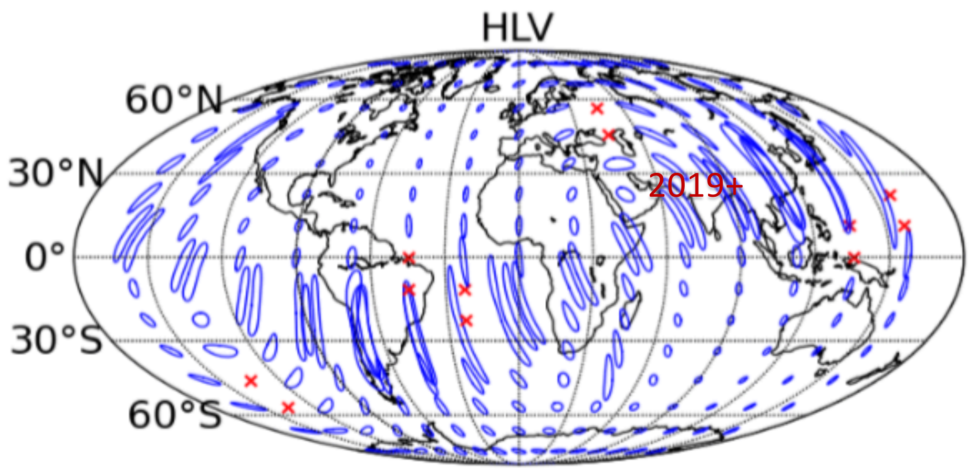
BNS Disruption & Post-Merger Physics

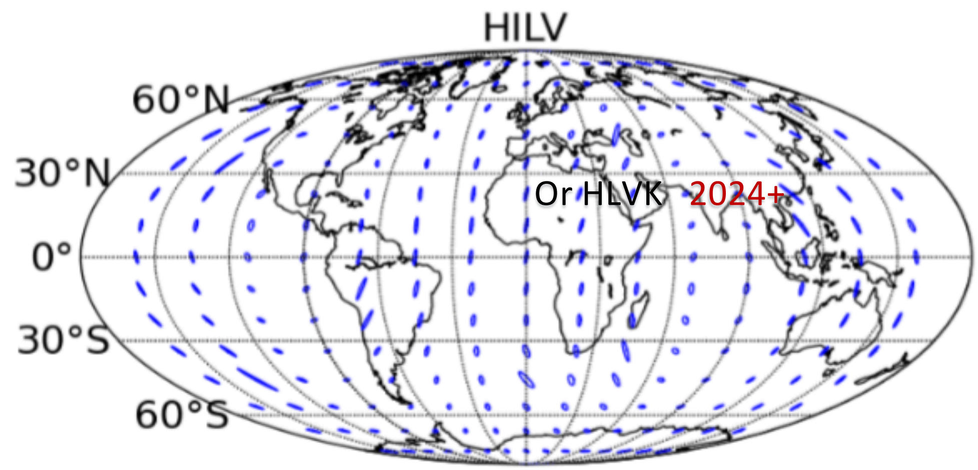


BNS @ 100 Mpc
Read, Schmidt, Clark and Lackey, G1700453
Read et al, Phys. Rev. D 88, 044042 (2013)

Improving Localization with four detectors







120 – 180+ deg^2 across the sky.

~10 deg^2 over the entire sky.

Abbott, B.P et al. Living Rev Relativ (2018) 21: 3. https://doi.org/10.1007/s41114-018-0012-9

Plausible observing schedule, expected sensitivities, and source localization with the Advanced LIGO, Advanced Virgo and KAGRA detectors

Epoch			2015 – 2016	2016 – 2017	2018 – 2019	2020+	2024+
Planned run duration			4 months	9 months	12 months	(per year)	(per year)
Expected burst range/Mpc		LIGO	40 – 60	60–75	75–90	105	105
		Virgo	–	20–40	40–50	40–70	80
		KAGRA	–	–	–	–	100
Expected BNS range/Mpc		LIGO	40–80	80–120	120–170	190	190
		Virgo	–	20–65	65–85	65–115	125
		KAGRA	–	–	–	–	140
Achieved BNS range/Mpc		LIGO	60–80	60–100	–	–	–
		Virgo	–	25–30	–	–	–
		KAGRA	–	–	–	–	–
Estimated BNS detections			0.05–1	0.2–4.5	1–50	4–80	11–180
Actual BNS detections			0	1	–	–	–
90% CR	% within	5 deg^2	< 1	1–5	1–4	3–7	23–30
		20 deg^2	< 1	7–14	12–21	14–22	65–73
	Median/deg^2		460–530	230–320	120–180	110–180	9–12
Searched area	% within	5 deg^2	4–6	15–21	20–26	23–29	62–67
		20 deg^2	14–17	33–41	42–50	44–52	87–90

Abbott, B.P et al. Living Rev Relativ (2018) 21: 3. https://doi.org/10.1007/s41114-018-0012-9

Longer Term:

Facility-limited '2.5 Generation' Detectors

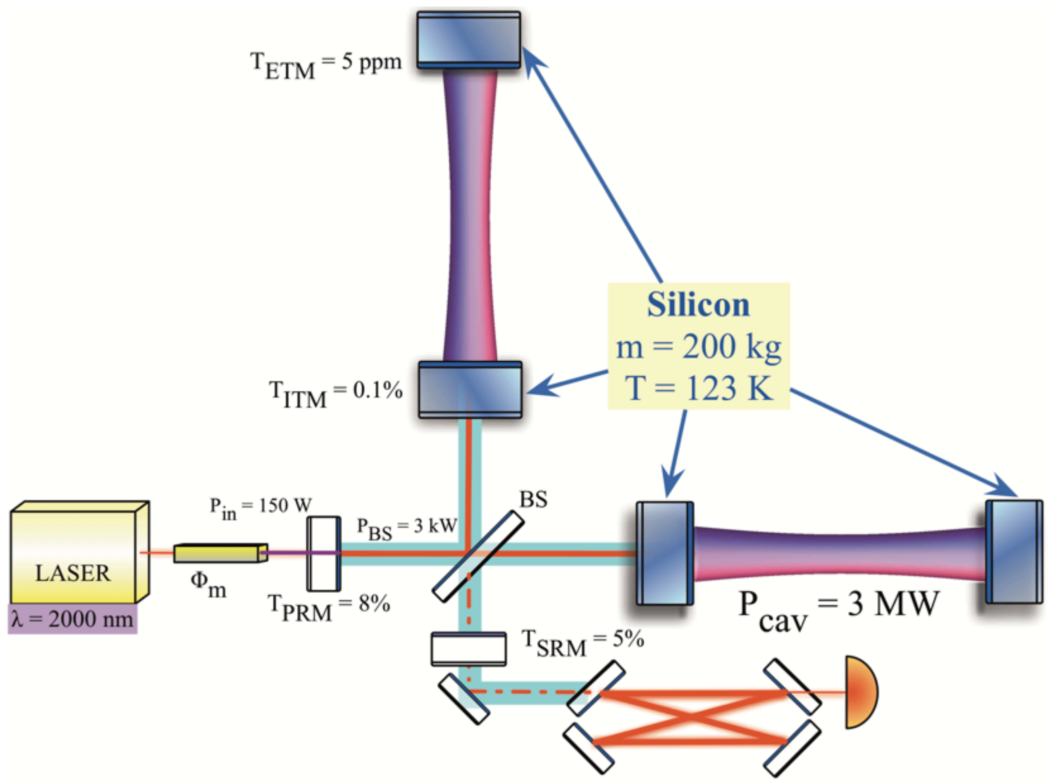
New '3rd Generation' Gravitational-wave Observatories

3G GW detector White Papers
Submitted to Astro2020
(2020 Astronomy and Astrophysics Decadal Survey)

https://arxiv.org/abs/1903.09220
https://arxiv.org/abs/1903.09277
https://arxiv.org/abs/1903.09221
https://arxiv.org/abs/1903.09260
https://arxiv.org/abs/1903.09224
https://arxiv.org/abs/1903.04615

Voyager: Facility-limited LIGO Detector

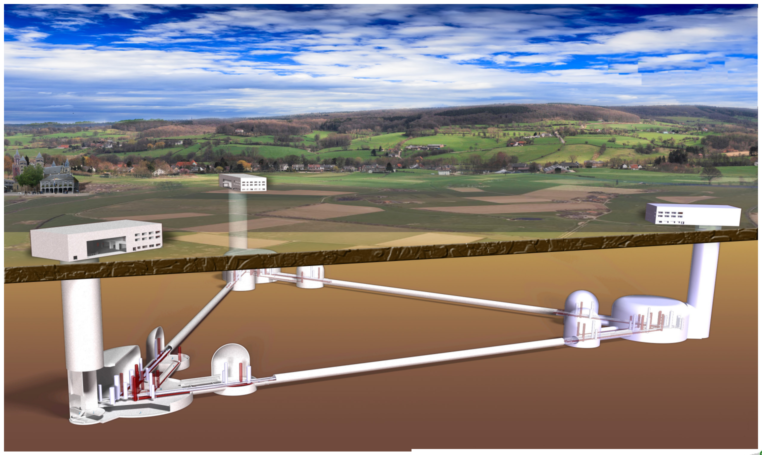
- *Voyager Key Technologies*
  - **Silicon Mirrors**: 200 kg, 45 cm dia., mCZ process
  - **Mirror Coatings: α**-Si/SiO_2 (**α**-Si: ~lossless thin film)
  - **Cryogenics:** 123 K (zero CTE), radiative (non-contact) cooling
  - **Lasers (2000 nm):** P~ 180 W, P_{ARM} ~ 2800 kW
  - **Wavefront Compensation:** thermally adjustable lenses only (no actuation of test mass)
  - **Photodiode Quantum Efficiency:** 80 -> 99% for 2 micron



- *Effort Led by R. Adhikari*

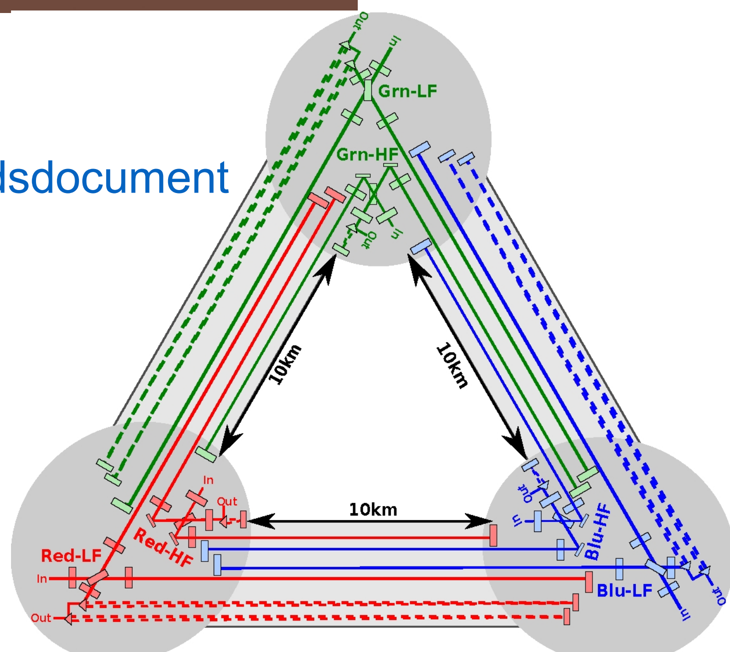
Einstein Telescope (Europe)

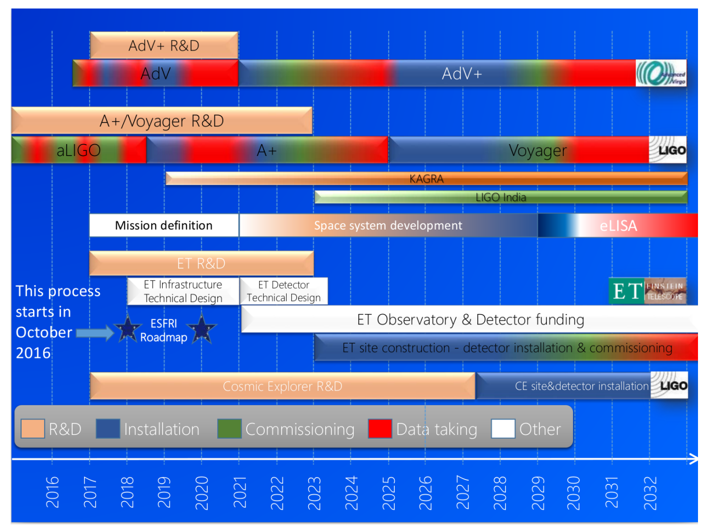
Slide Credit:
Vaishali Adya, AEI



- Third-generation GW observatory
- Target sensitivity for ET a factor of ten improvement in comparison to current advanced detectors
- 10 km long, Underground
- Xylophone configuration, 6 interferometers

Formal Design Study completed in 2011:
http://www.et-gw.eu/etdsdocument

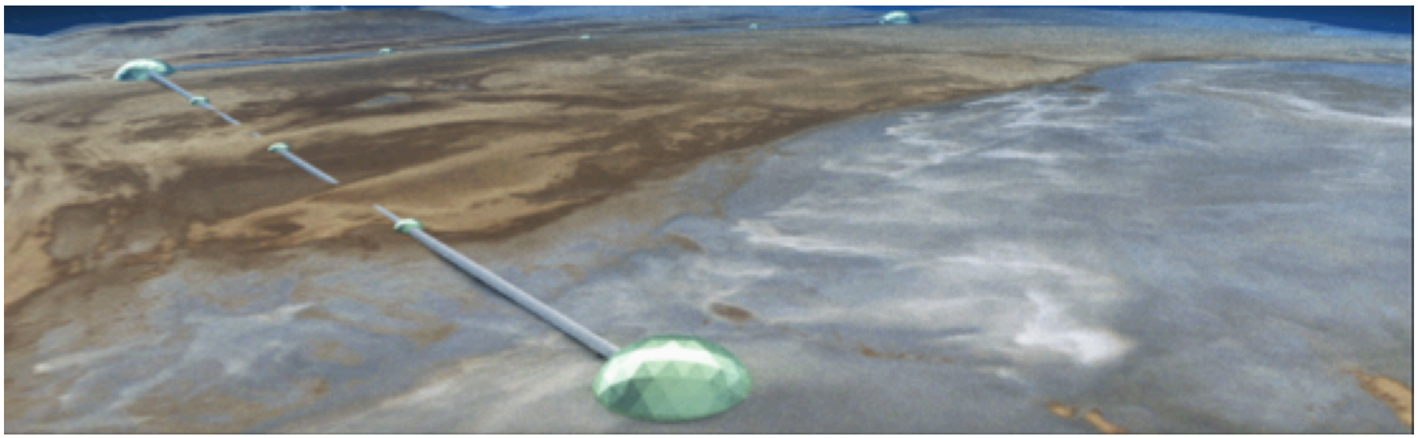




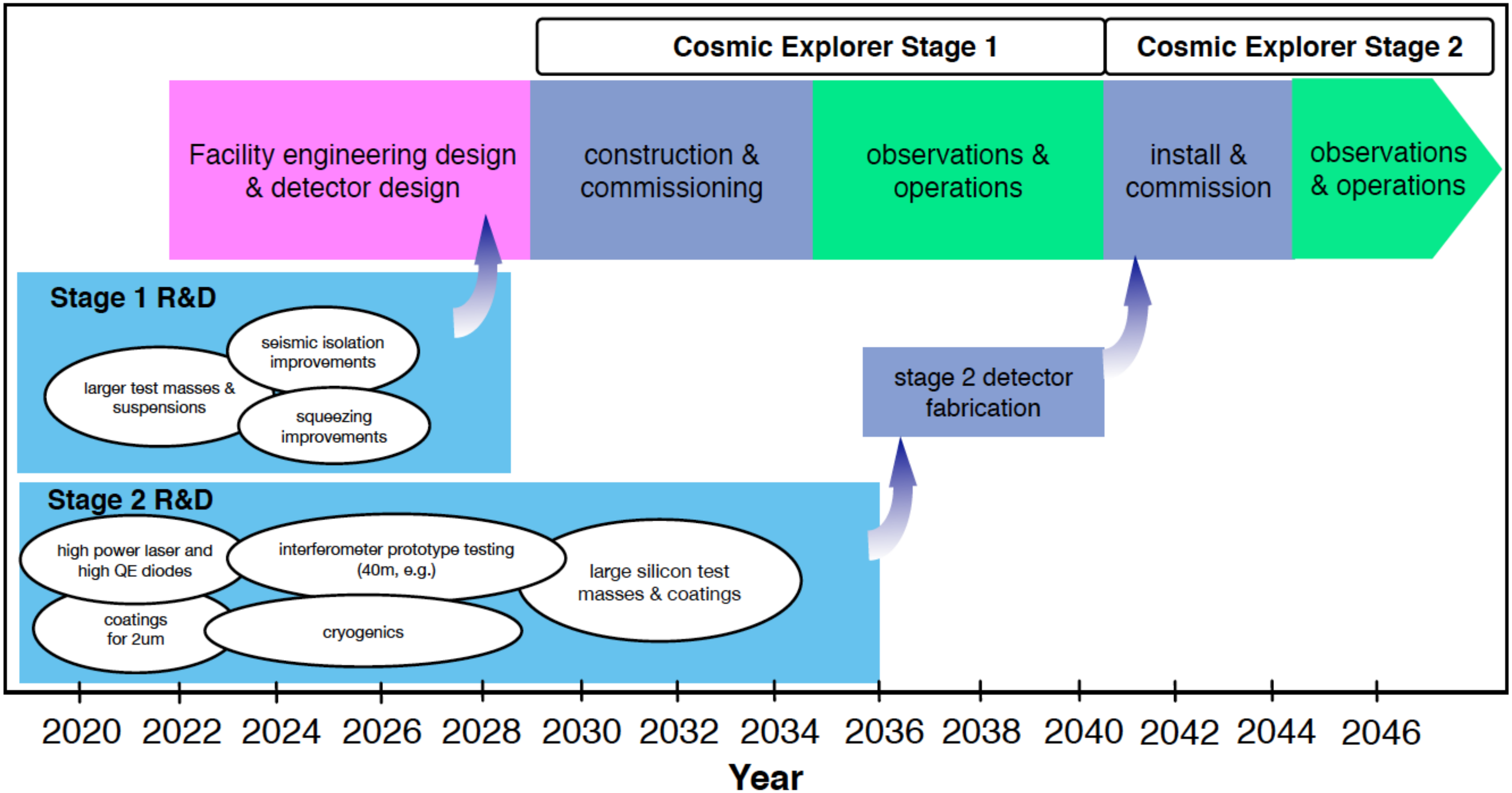
Cosmic Explorer (US)

- Third-generation GW observatory
- Target sensitivity a factor of > 10 improvement in comparison to current advanced detectors
- Above ground, 40 km arm length, L configuration

Formal design study under way (M. Evans, MIT, lead PI)
cosmicexplorer.org

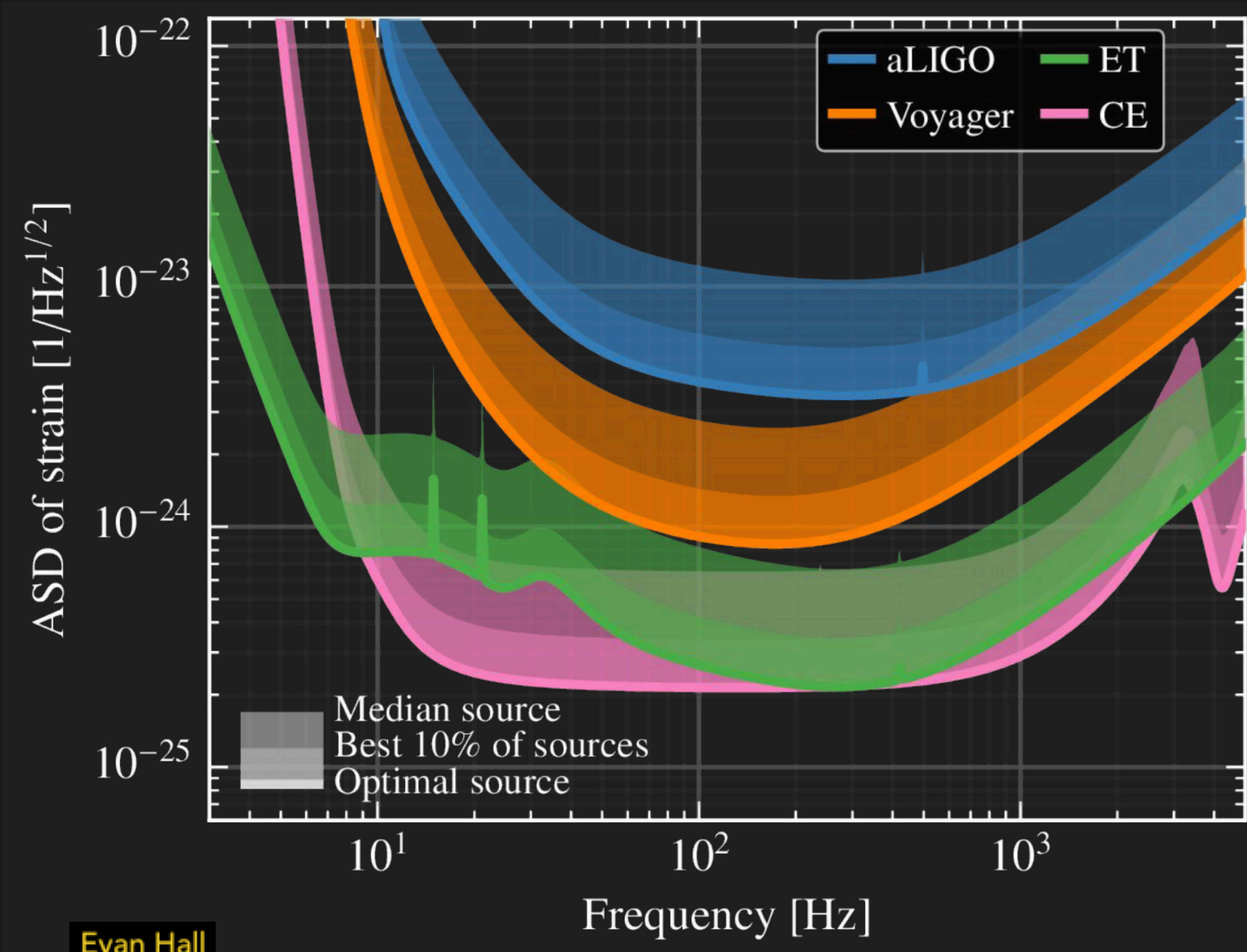


Timeline of a Cosmic Explorer 40km Observatory



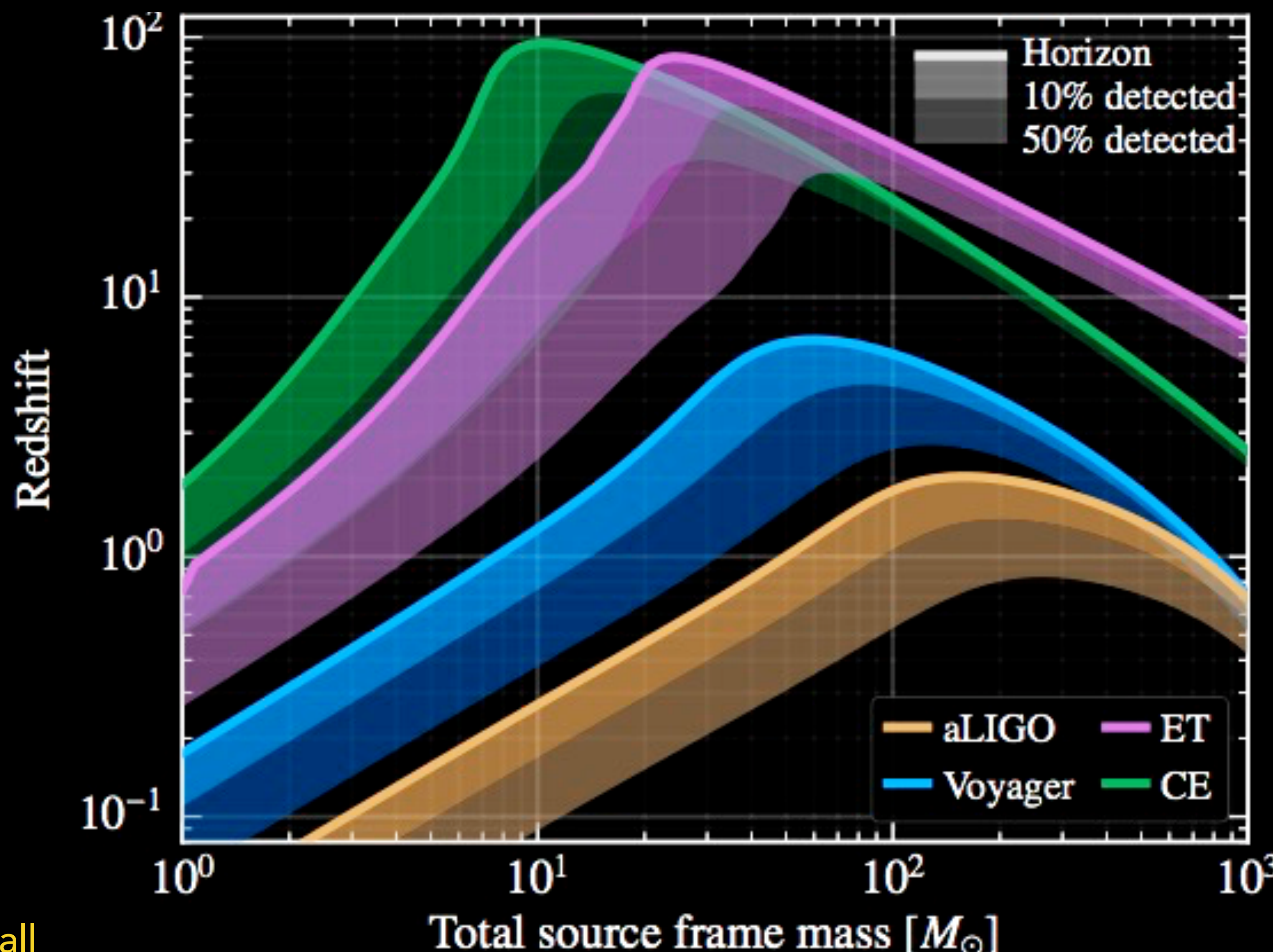
https://arxiv.org/abs/1903.04615

Detector Sensitivities

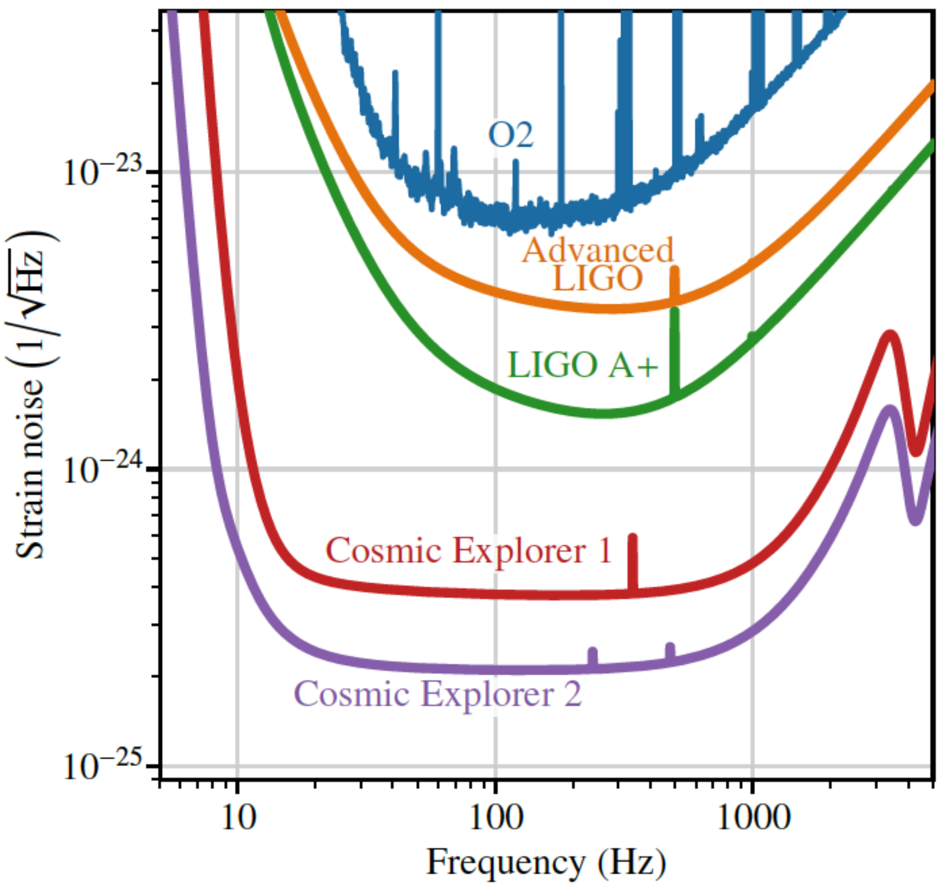


Evan Hall

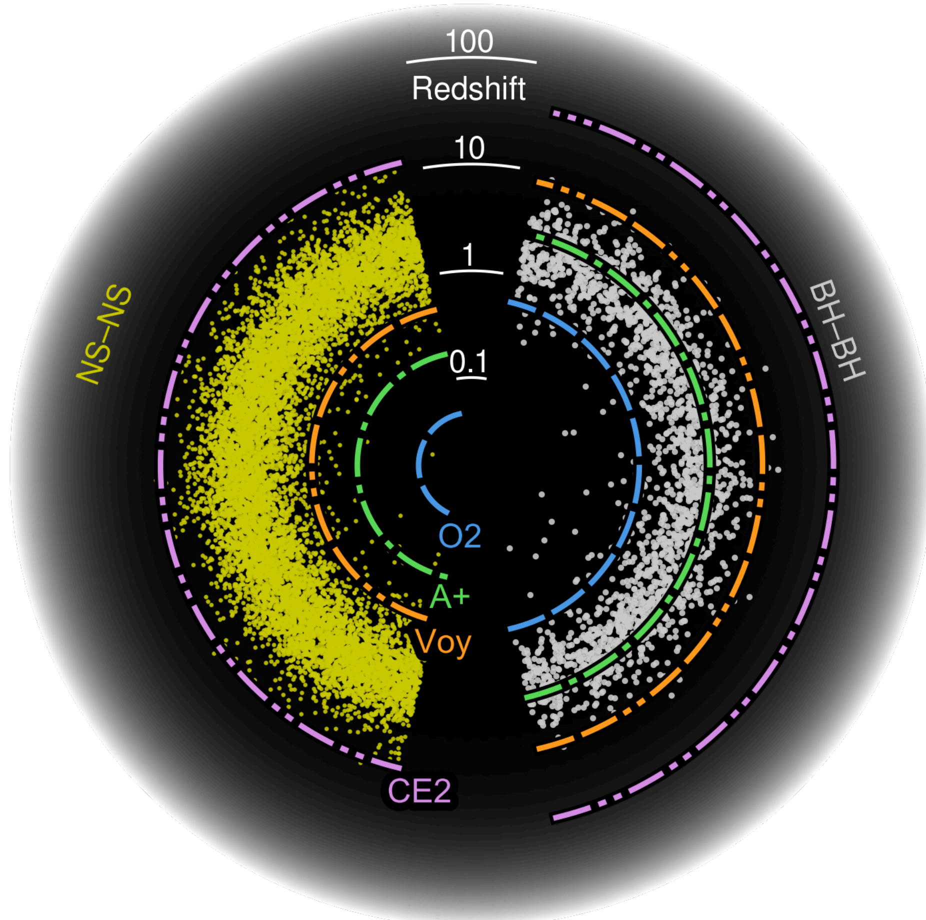
OBSERVING EARLIEST MOMENTS OF FORMATION OF STARS AND STRUCTURE



Evan Hall



https://arxiv.org/abs/1903.04615



https://dcc.ligo.org/LIGO-G1900803/public

Let’s build up a close and tight connection between GW detection and LSST, to maximize the science!